THE LOWER AND MIDDLE PALAEOZOIC STRATIGRAPHY AND SEDIMENTARY TECTONICS OF THE SOFALA-HILL END-EUCHAREENA REGION, N.S.W.

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(Plates IX–XII)

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Synopsis

Ordovician andesitic volcanics are the oldest rocks in this region of about 1,000 square miles. They are overlain about Sofala in the east of the region, by Silurian limestones and shales, rhyolitic volcanics, subgreywackes, dacitic tuffs and further subgreywackes, and west near Euchareena by rhyolitic volcanics, limestone and shale. The source of the sediments lay to the west and south-west except for the highest subgreywacke unit in the Sofala sequence which was derived from the underlying formations as a result of the uplift of a structure to the east (the Capertee Geanticline). Dacitic vulcanism on this geanticline in the early Devonian provided directly or indirectly, much of the detritus comprising the greywackes and tuffs of the Crudine Group and the Merrions Tuff which were deposited in the Hill End Trough in the Sofala-Hill End area. In the Euchareena district more restricted andesitic and dacitic vulcanism occurred at this time. During the later Lower Devonian and perhaps part of the Middle Devonian, greywacke sedimentation took place in the Hill End Trough while limestones and shales were deposited in the Limekilns area. Near Euchareena limestones, shales and lithic calcarenites were being laid down. The youngest rocks deposited in the region prior to the Upper Devonian are acid tuffs overlying the limestone-shale sequence at Limekilns perhaps unconformably. The region is folded into a broad synclinorium which has a culmination in the vicinity of Hill End and is overthrust to the east near Sofala. The rocks of the central part are strongly cleaved and belong to the green schist metamorphic facies.

INTRODUCTION

The region of over a thousand square miles, described in this paper contains folded strata ranging in age from Ordovician to Devonian. Within the region there are three palaeogeographic and tectonic entities (Figure 1), which have been discussed in previous publications (Packham, 1960, 1962, 1968). They are from east to west, the Capertee Geanticline, the Hill End Trough and the Molong Geanticline. This paper presents the stratigraphic evidence on which the recognition of these features was originally based.

Within the Capertee Geanticline, which came into existence at about the end of the Silurian, the sediments are normally uncleaved and only moderately folded. Limestones occur in the Lower Devonian and indicate that shallow water environments occurred in that part of the succession at least. The geanticline has as its western boundary the Wiagdon Thrust, a structure which is now known to extend from north of Mudgee to south of Yetholme, a distance of about 100 miles.

The Hill End Trough which occupies most of the region under discussion contains greywacke-type sediments throughout the exposed Silurian and Devonian section. Folding is moderate to strong, with slaty cleavage developed everywhere in the finer sediments and in the coarser rocks in the central part of the trough. The cleavage fans on a regional scale, dipping to the west in the eastern part and east in the west. It is approximately vertical in the vicinity of Hill End. The highest grade of metamorphism reached is in the central part of the trough where biotite is developed over a width of about 10 miles across the strike. On the western side of the trough, the greywacke sequence passes into fossiliferous sediments on the eastern flank of the Molong Geanticline where limestones occur in the Ordovician, Silurian and Devonian Systems.

The region is one in which outcrop is generally good. It is essentially a plateau with an elevation of about 3,200 feet in the east and 2,500 feet in the west, strongly dissected by the Turon and Macquarie Rivers and their tributaries. Exposures along the rivers and the major tributaries are excellent.

The description of the stratigraphy is divided into three sections (a) the Sofala-Limekilns district of the eastern side of the Hill End Trough and the western edge of the Capertee Geanticline (*b*) the Hill End district, in the centre of the trough and (*c*) the Euchareena district on the western side of the trough and the eastern side of the Molong Geanticline.

Rock specimens mentioned in the text are in the rock collection of the Department of Geology and Geophysics, University of Sydney.

The Stratigraphy of the Sofala–Limekilns District

In the Sofala district there is an essentially conformable sequence of strata, ranging in age from Upper Ordovician at the base to possibly Middle Devonian at the top. The highest unit in the Limekilns area, the Winburn Tuff, may be unconformable on the Limekilns Group. The successions in the Sofala-Turondale area and the Limekilns area are as follows (in descending order):

Sofala-Turondale		Limekilns	
		Winburn Tuff	2000+′
Cunningham Formation	2800′	Limekilns Group	2500′
Merrions Tuff	2000′	Merrions Tuff	1500′
Crudine Group	3700′	Crudine Group	2500′
Cookman Formation	1500′	Cookman Formation	600′
Chesleigh Formation	3500′	Chesleigh Formation	3500′
Bell's Ck. Volcanics	1500′	————	
Tanwarra Shale	250′	Tanwarra Shale	0–250′
Sofala Volcanics	?	Sofala Volcanics	7000+′

The Limekilns sequence is east of the Wiagdon Thrust and the Sofala sequence is west of this fault in the Hill End Trough.

Sofala Volcanics

The type section of the Sofala Volcanics is exposed along the Turon River, commencing one and a half miles west of Sofala, extending ten miles to the east where the formation is thrust over Upper Devonian sandstones. No underlying formation has been recognized so that the base of the Sofala Volcanics cannot be defined. In the type section, approximately 7,000 feet of strata consisting dominantly of clastic and pyroclastic detritus with a small proportion of lavas, are exposed. Occasional horizons of chert represent concentrations of pelagic elements.

Type section. In the lower part of the section medium to fine-grained sediments are dominant, typically in beds a foot thick, displaying graded bedding, convolute bedding and slump structures. Fine-grained sediments in the section are very dark grey to black in colour and have a sub-conchoidal fracture. Three types of coarser sediments occur in the section. There are breccias containing a small amount of matrix, composed almost entirely of fragments of rocks of the same lithology as the fine-grained sediments in the section (Plate IX, fig. 1). The second type consists of an abundant fine-grained matrix including rounded cobbles and boulders of andesite and siltstone blocks up to a foot or so in diameter. The third kind, composed of angular blocks of intermediate lavas occurs sporadically in the lower part of the type section but is abundant in the upper part. About the middle of

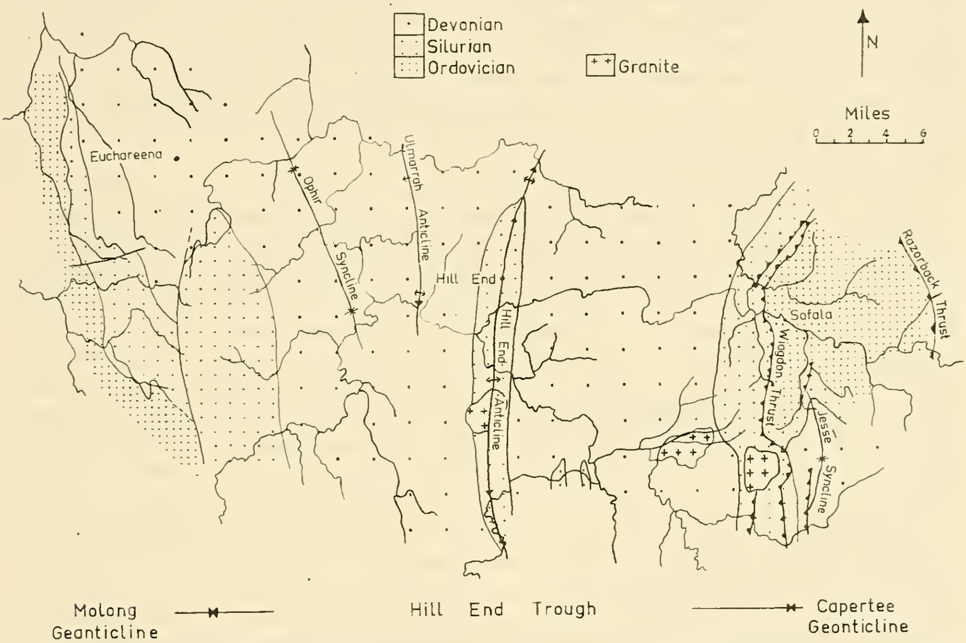

Figure 1. General regional map showing distributions of Ordovician, Silurian and Devonian Systems and major structures and tectonic units mentioned in the text.

the sequence (about 2½ miles east of Sofala) there is a chert horizon several hundred feet thick which extends north and south of the Turon River for several miles.

The upper part of the formation consists almost entirely of tuffs, abundant andesite breccia and some andesites. West of Sofala these are transgressed by dykes and other minor intrusions of rocks of lamprophyre affinities, apparently basic differentiates of the andesites. The increase in the coarseness of the volcanics and the presence of the related intrusives suggest that the vent (or vents) responsible for the deposition of the upper part of the section may have been close at hand.

Regional distribution and variation. In the upper part of the sequence, limestone blocks occur in breccias in Big Oaky Creek just east of Wattle Flat, and a limestone lens occurs one and a half miles north-north-west of Wattle Flat. The limestones may have resulted from the rapid building up of volcanic debris in the upper part of the section. Apart from this, the formation maintains the general characteristics of the type section throughout its outcrop.

Except in close proximity to the Wiagdon Thrust where cleavage is developed, the rocks of the Sofala Volcanics are massive and indurated. Even the fine-grained sediments have little tendency to split along bedding planes. Small movements along joints are observable in almost every outcrop.

Petrography. Apparently most of the lavas of the Sofala Volcanics were originally andesitic. They contain phenocrysts of plagioclase, augite and/or hornblende. Occasional lavas have groundmasses containing small plagioclase laths but in most the groundmass is very fine and even grained. These latter may have been originally glassy. The plagioclase in all the thin-sections which were examined is albite. The ferromagnesian minerals are fresh in most rocks, except in the area north-west of Sofala. Two types of hornblende occur in the relatively unaltered rocks; green hornblende with a pleochroic scheme, Z = olive green, Y = yellow green, and X = pale yellow with $Z \wedge C$ about 24° and brown with $Z \wedge C$ about 18°. The green amphibole often shows signs of resorption and the brown amphibole occasionally contains inclusions of pyroxene. The pyroxenes are pale green in thin section and have a moderate 2V and an extinction of about 45°.

The lamprophyres which occur to the west of Sofala are petrographically very similar to the andesites except for the absence of felspar phenocrysts. An almost identical association has been described from the Wellington District by Basnett (1942). The Sofala lamprophyres are amphibole-rich, but at least some of this replaces pyroxenes as is evidenced by the typical pyroxene form of some of the amphibole crystals and the presence of rare irregularly shaped cores of pyroxene. The replacing mineral has a $Z \wedge C$ of 20° and X = colourless, Y and Z = pale green. This mineral also replaces darker amphibole in which X = yellow, Y = brown and Z = brownish green and $Z \wedge C$ is about 27°. The groundmasses of these rocks are highly altered, now consisting of albite, pale green amphibole and epidote with calcite abundant in some.

The volcanic breccias are composed almost entirely of fragments of various types of andesites. There is no sign of rounding even in the larger fragments. The matrix consists of small rock fragments and grains of felspar and pyroxene. Near the top of the succession where there is considerable alteration, it is not clear whether those rocks containing angular blocks up to several inches across are actually lavas including fragments of andesite similar to those described by Basnett and Colditz (1946) from rocks of comparable age at Wellington, or whether they are actually breccias. The presence of numbers of clastic fragments in some localities suggests an original sedimentary origin for the rocks. The matrix in which the fragments now occur is composed of an interlocking mass of albite, epidote and pale green amphibole. In the lower part of the sequence, relatively unrecrystallized breccias consist of fragments of lavas (generally a variety of types), pale green pyroxene a little felspar (albite) in a matrix of chlorite, calcite and epidote.

Like the breccias, the rocks of intermediate grainsize consist almost entirely of volcanic material. Except in the upper part of the formation where the bedding is obscure, the sandy sediments are greywackes. They are poorly sorted. Felspar (albite) is the dominant mineral, the grains are either idiomorphic or broken crystal fragments. Green and brown hornblende and augite are present. A little quartz occurs, this shows signs of magmatic corrosion and is hence probably volcanic in origin. Rock fragments are rare, those present are grains of the groundmass of andesite. The matrix, which usually comprises some 20 percent of the rock, is composed of chlorite, albite and a little calcite.

The finer grained rocks have a mineralogy similar to that of the arenites. The finest of these sediments are chert-like in hand specimen and are difficult to distinguish from the occasional radiolarian cherts which occur throughout the sequence. The radiolarian rocks themselves, consist of poorly preserved radiolaria, making up roughly 10 percent of the rock, in a fine-grained groundmass of material showing weak double refraction and a refractive index higher than canada balsam—presumably quartz. Large numbers of minute black granules, possibly carbonaceous, and a few percent of albite and chlorite grains of silt size are scattered through the fine groundmass of the radiolarian rocks. Several series of quartz veins must have been deposited soon after deposition of the sediment since where fragments of the radiolarian rocks are incorporated in intraformational breccias, they sometimes contain quartz veins predating their incorporation (Plate IX, fig. 1). If the fragments were derived from older formations it is most unlikely that in such a sediment all the fragments would be angular and of precisely the same lithology as the finer sediments in the Sofala Volcanics. Deformation seen in some of the early formed veins in the radiolarian rocks is probably the result of the continuation of compaction of the sediment after the formation of veins.

Depositional environment and direction of origin. The association of sedimentary structures in the lower part of the Sofala Volcanics is as follows: graded-bedding, convolute-bedding and slump structures. Cross bedding is absent. This association together with the presence of graptolites and radiolarian cherts suggests a deep water environment of deposition.

The beds of coarse sediment with rounded andesitic cobbles and boulders with a large proportion of matrix are not simple pyroclastic sediments. The rounding of the andesite cobbles indicates some transportation before final deposition. Slumping or some form of mass movement seems to be the only way to explain the association of these sediments with what are almost certainly deep water sediments. Contemporaneous movements have resulted in the breaking up of some of the fine-grained sediments of the sequence resulting in breccias composed almost entirely of fragments of those rocks.

Towards the top of the formation the appearance of limestone in blocks and lenses suggests that there was some shallowing which may be due to orogenic movement, local volcanic accumulation or filling of the entire basin.

Slump structures observed in the type section, a short distance upstream from Eaglehawk Gully indicate movement from west to east. Thus an easterly sloping sea floor can be inferred.

Age. Poorly preserved graptolites have been found about the middle of the Sofala Volcanics in Eaglehawk Gully. The graptolites appear to be *Glyptograptus teretiusculus* which is found in uppermost Darriwillian and Gisbornian strata. If this identification can be relied upon, then it is probable that much of the Ordovician is represented by the volcanics since the graptolites occur a little below the middle of the exposed section of the formation. The top of the formation pre-dates the Tanwarra Shale, the age of which, from the contained graptolites and other lines of evidence, is probably Upper Llandovery or early Wenlock. The upper possible limit of the Sofala Volcanics is within the Lower Silurian.

Tanwarra Shale

This formation rests, with a slight break, on top of the Sofala Volcanics. The junction of the two formations is obscured in many localities by overthrust faulting on the Wiagdon Thrust. The base of the Tanwarra Shale is marked by a conglomerate or sandstone resting on top of the Sofala Volcanics.

This basal member is composed almost entirely of material derived from the erosion of the andesites, together with some fossil detritus.

Type section. The type section of the formation is in Portion 516 of the Parish of Sofala, in the headwaters of Spring Creek and Bell's Creek, south of Mount Tanwarra after which the formation is named. This section is 250 feet thick. The basal conglomerate is of the order of forty feet in thickness and contains limestone pebbles with "*Halysites*" in addition to andesitic detritus. Above, is an impure limestone about twenty feet thick. This limestone consists of alternating bands of fossil material and sandy calcareous shale. The larger coral fossils are preserved in their living environment or have been transported only a short distance. The fauna is as follows: *Phaulactis shearsbyi*, *Mucophyllum liliiforme*, *Heliolites daintreei*, *Acanthohalysites* cf. *gamboolicus*, *Alveolites* sp., *Atrypa* sp., cf. *Barrandina* sp. and *Encrinurus* sp. Above this horizon there are a few feet of shales and sandy shales. The shales which make up the remainder of the formation are green, grey and black in colour, all are poorly bedded and contain occasional fossil remains, mostly poorly preserved small brachiopods. Ten feet above the limestone there are sparse graptolite remains. The forms present are: *Monograptus* cf. *paradoxus* and *M. priodon.*

The top of the formation is recognised by the appearance of bands of acid tuff marking the beginning of the Bell's Creek Volcanics.

Regional distribution and variation. North of the type section, the formation is considerably sheared. The stratigraphy of the formation in this area is not clear. It is possible that north of the Turon River some of the rocks mapped as Tanwarra Shale may actually be Chesleigh subgreywacke. The sediments are rolled out to such an extent that in many exposures bedding has been completely destroyed and replaced by a crude alternation of silty and shaly material parallel to the cleavage.

To the south of the type section there is a small outcrop of fossiliferous marl a mile to the west of the top of Wiagdon Hill which may be a southwards continuation of the formation; from this *Encrinurus* sp. was collected. At Wiagdon Hill on the Bathurst Road, the formation is represented only by a thin limestone and some shales; this is on the overthrust side of the Wiagdon Thrust. In the creeks to the south-east along the strike the formation is missing, apparently faulted out. Underlying the Bell's Creek Volcanics three miles south of Wiagdon Hill there is a sequence of shales representing a continuation of the Tanwarra Shale.

There is only one known occurrence of the Tanwarra Shale on the eastern side of the fault. This is in the head of the Spring Creek in Portion 245 of the Parish of Sofala near the western border of Portion 253, three and a quarter miles east of Wattle Flat. The succession is similar to that of the type section four and a half miles to the west, except that graptolites have not been found at this second locality. The fauna includes: cf. *Phaulactis shearsbyi*, *Mucophyllum crateroides*, *Tryplasma* sp., *Spirinella caecistriata* and *Encrinurus* sp. Fossils are considerably more abundant and better preserved than in the type section.

In the sections east of the Wiagdon Thrust where the Tanwarra Shale is absent the Sofala Volcanics are followed by a breccia composed of andesitic detritus. This is succeeded by the Chesleigh Formation without the intervention of the Bell's Creek Volcanics.

Age. The age of the formation is clearly Silurian. If the *Monograptus* cf. *paradoxus* is in fact *M. paradoxus* then the age is almost certainly Upper Llandovery; if not, then the age could be anywhere from the base of the

Upper Llandovery to half way up the Wenlock. The presence of "*Halysites*" in the shelly fauna is also in agreement with an age in the lower half of the Silurian.

Bell's Creek Volcanics

The Bell's Creek Volcanics is a succession of rhyolitic tuffs and lavas which conformably overlies the Tanwarra Shale. The formation varies considerably in thickness along the strike and is confined to the western side of the Wiagdon Thrust.

Type section. The type section, 1,500 feet thick, is exposed in the valleys of Bell's Creek and Jew's Creek, two miles south-west of Sofala. This is the maximum thickness known for the formation. The basal part consists dominantly of tuffs, succeeded by rhyolite and then by another tuffaceous unit. Overlying is the Chesleigh Formation, the lower part of which is non-volcanic. The lavas of the Bell's Creek Volcanics form a high ridge to the west of Bell's Creek while the underlying tuffs and a dolerite sill occupy the floor and the eastern side of the valley. The tuffs at the top of the formation occupy the small valley of Middle Creek to the west of the ridge of rhyolites.

Regional distribution and variation. North of the Turon River the formation is considerably diminished in width as a result of thrust faulting. It is possible that the contact between the Bell's Creek Volcanics and the Tanwarra Shale north of the Turon River might be a tectonic one.

The Bell's Creek Volcanics outcrop in the Wiagdon Hill road section as tuffs, slates and chert-like rocks. Half mile to the south-east very poorly preserved graptolites occur in a cherty shale in the formation. They are straight monograptids but no further identification is possible. Further south in the vicinity of Cheshire's Creek, lavas are once more abundant. The volcanics can be traced for eighteen miles along the strike but to the east of the Wiagdon Thrust the formation is unknown. This is unexpected in view of the considerable extension of the volcanics along the strike and it is the first indication of a significantly different stratigraphic succession on either side of the thrust.

Petrography. The rhyolites are pale green or buff coloured rocks with a subconchoidal fracture. Flow-banding is only rarely visible in hand specimen. In thin section these rocks have either a uniform groundmass or irregular flow structure. Phenocrysts, which are not abundant, are dominantly quartz and orthoclase, with minor amounts of albite (about Ab_{95}). Idiomorphic phenocrysts are rare, mostly they are corroded or fractured. Ferromagnesian minerals, present in only small quantities, are confined to the groundmass. They are either biotite, pleochroic from yellow to very dark brown, or chlorite, which is apparently the alteration product of the biotite. Epidote and clinozoisite are present in some rocks occurring as small individual crystals scattered through the rock and as aggregates up to 1 mm. across. The lavas are cut by quartz veins some of which also contain clinozoisite or epidote. The groundmass shows a good deal of textural variation even within the one section; it varies from a very fine-grained to a coarse-grained mosaic of interlocking quartz and felspar grains.

The tuffaceous lithologies in the formation range from coarse breccias to extremely fine-grained rocks with a flinty appearance. Their mineralogy is similar to that of the rhyolites with which they are associated. The medium-grained tuffs are composed of broken quartz and felspar grains, biotite and devitrified glass shards, together with a little apatite. The finer tuffs are banded with some evidence of graded-bedding on a small scale. The extremely fine-grained tuffs are generally pale green flinty rocks, without bedding in hand specimen or with broadly developed irregular banding. In thin-section these are seen to consist of an interlocking mass of quartz and felspar with some calcite, chlorite and epidote.

Chesleigh Formation

The Chesleigh Formation takes its name from the property "Chesleigh" (three miles west of Sofala) on which it outcrops as a prominent strike ridge and conformably overlies the Bell's Creek Volcanics. It is non-volcanic in the lower part of its section, thus the base can be defined as the top of the last tuff horizon.

Type section. The formation is 3,500 feet thick in this section which is that exposed along the Turon River in Portions 48, 47 and the eastern part of Portion 46 of the Parish of Waterbeach. The lowest unit, a massive subgreywacke, 2,000 feet thick, outcrops on the south bank of the Turon River and forms a large cliff in which bedding is poorly defined. Overlying this is 500 feet of interbedded slate and subgreywacke. The beds vary from a few inches to ten feet in thickness. In the top thousand feet of the formation, the amount of felspar increases, subgreywackes pass into greywackes and there are some interbedded crystal tuff horizons in which the beds are up to twenty feet thick. The uppermost beds are thinly bedded fine-grained felspathic siltstones and slates. These siltstones which are green and red are followed by the first of the quartz-rich sediments of the Cookman Formation.

Regional distribution and variation. In spite of the large size of outcrops along the Turon River, there is very little fresh rock exposed in the type section. Two miles to the north, on Two Mile Creek, the bedding characteristics of the lower massive subgreywacke can be seen. Bedding planes are spaced six to eight inches apart and each bed is to some extent graded. The clarity of this grading is obscured by the small size range—from fine sandstone to siltstone. The bedding features are further obscured as a result of tectonic movement which has taken place within the formation. This movement is particularly evident on the banks of Crudine Creek between Two Mile Creek and the Turon River, where slaty cleavage is strongly developed in interbedded slates and subgreywacke. To the south of the type section, the subgreywacke lithology is dominant and the upper tuffaceous part of the formation consists only of slates and fine tuffs with a cherty appearance.

The Chesleigh Formation occurs on the eastern side of the Wiagdon Thrust with lithology and thickness similar to those of the type section, but differing in that cherty rocks are common in the upper part of the formation. In this region, the Chesleigh Formation rests directly on the Sofala Volcanics except in the headwaters of Spring Creek where the Tanwarra Shale occurs. The contact between the Tanwarra Shale and the Chesleigh Formation in this area has not been observed.

The absence of the Bell's Creek Volcanics and the restriction of the Tanwarra Shale on the eastern side of the Wiagdon Thrust, suggests that the base of the Chesleigh Formation in that area is an erosional surface. The extension of the missing formations along the strike is such that they might be expected to continue across the strike as well. However, it has been already pointed out that the Bell's Creek Volcanics vary considerably from place to place. Similarly, since the Tanwarra Shale was, at least in part, laid down in a shallow water environment, it may perhaps have not been deposited in some localities. Breccia composed of andesitic material underlying the Chesleigh Formation east of Wattle Flat, mapped as part of the Sofala Volcanics, might be the time equivalent of the Tanwarra Shale. Even if there is no erosional break below the Chesleigh Formation, the significant feature is that the Wiagdon Thrust brings into juxtaposition two significantly different stratigraphic sequences. Differences between the sections on either side of the thrust are maintained in most of the formations overlying the Chesleigh Formation.

Petrography. In the type section the subgreywacke (Plate IX, fig. 2) which makes up the lower part of the formation contains fifty to seventy percent of quartz. Most of the grains show some sign of rounding, though this is more evident in the largest grains (0·5 mm.). The sorting is poor, all gradations exist between the largest grains and the finest material constituting the matrix. This matrix makes up twenty percent or more of the rock. Apart from quartz silt, the matrix is composed of chlorite and pale green, weakly pleochroic mica. A small proportion of rock fragments is present; these fragments are of two types. Firstly, shales consisting of a fine-grained aggregate of quartz, chlorite and sericite and in some cases a little carbonate. Secondly, there are fragments composed of interlocking quartz grains with small amounts of chlorite either included in the grains or concentrated in their margins. These latter rock fragments are probably fragments of thermally metamorphosed sediments. Felspar is absent. In the matrix there are occasional grains of muscovite. The heavy mineral assemblage is varied and includes: tourmaline (variety of shapes, sizes and colours), zircon, sphene, apatite and rutile.

In the upper part of the formation, the rocks which have been called greywackes differ from the underlying subgreywackes only in the addition of felspar and a corresponding decrease in the percentage of quartz. Orthoclase is more abundant than plagioclase (albite).

The tuffs of the Chesleigh Formation are massive with grainsizes ranging from fine sand to breccias. Their interpretation in thin-section is difficult. There is a good deal of secondary albite in the matrix and replacing orthoclase, as well as in veins. Quartz and carbonate are the abundant secondary minerals in some specimens while in others the assemblage is albite, quartz and epidote. The detrital minerals are quartz, orthoclase, plagioclase (now albite) and chlorite. In some of the coarser rocks fragments of acid porphyritic rocks occur.

The lithology of the formation on the eastern side of the Wiagdon Thrust is very similar to that of the type section. Some of the subgreywackes however, contain a small proportion of felspar (orthoclase and albite), and have a greenish colour in hand specimen instead of the normal grey colour. The variation of colour is attributable to the presence of additional chlorite.

Depositional environment and origin of the detritus. A variety of sedimentary structures indicative of a deep-water depositional environment, are present in the Chesleigh Formation. They include graded bedding, load casts (Plate IX, fig. 8), small slumps, small-scale cross-bedding, and flute-casts. The last three structures have yielded evidence indicating the direction of slope of the seafloor at the time of deposition.

Small-scale slump structures occur near the top of the Chesleigh Formation in the type section and in Dam Creek, in fine-grained siltstone beds four to eight inches thick. The direction of movement which has been determined by measuring the inclination of a number of slump fold axes in each locality, is consistently towards the east-north-east.

A similar direction of movement is indicated by flute-casts beautifully exposed on the bases of overturned beds two miles north of Cheshire's Creek and a locality on Cheshire's Creek half a mile east of the Wattle Flat–Peel road. At the first locality the direction of movement is corroborated by the dip of small-scale cross-bedding in a similar direction.

The detritus in the lower part of the formation is apparently first or second cycle detritus derived from a granitic terrain. The low proportion of felspar and the presence of sedimentary rock fragments suggest the former rather than the latter. It is known that there were folding movements in the Tasman Geosyncline (the Benambran Orogeny) roughly at the end of the Ordovician Period and continuing into the Silurian (see Packham, 1967*a*). The Ordovician sediments exposed in the southern highlands of New South Wales by these movements were slates, shales and subgreywackes which were derived from granitic rocks directly or indirectly forming an ideal source for the detritus for the Chesleigh Formation.

In the upper part of the Chesleigh Formation acid volcanic material is common but detritus of the type which makes up the lower part of the formation is still present.

Fauna. No fossils have been found in this formation.

Cookman Formation

The Cookman Formation which consists of quartz-rich greywackes, occasional grits and conglomerates interbedded with slates overlies the Chesleigh Formation. Its base is recognized by the first appearance of the characteristic light-coloured quartzite-like subgreywacke and sublabile greywacke.

Type section. The type section of the Cookman Formation, one thousand five hundred feet thick, is in the eastern half of Portion 46 of the Parish of Waterbeach on the south bank of the Turon River immediately west of the type section of the Chesleigh Formation. The formation takes its name from the Cookman Range which is the strike ridge that the formation makes to the north of the Turon River. The type section consists dominantly of slates with interbedded fine-to-medium-grained sandstones and only a few beds of coarse sandstones and conglomerates. Most of the sandy beds, several inches to a foot thick, display no obvious internal structure, but the beds of the order of three feet thick are graded-bedded. Frequently, casts of worm-tracks appear on the under surfaces of the sandy beds. At the top of the formation there is a thick slate which is overlain by the lowest coarse-grained beds of the Crudine Group.

Regional distribution and variation. The Cookman Formation maintains the features of the type section along its strike. It can also be recognized east of the Wiagdon Thrust overlying the Chesleigh Formation. In Cheshire's Creek in the southern part of Portion 119 (Parish of Wiagdon), the formation is similar in lithology to the type section but only six hundred feet thick. It can be traced north from Cheshire's Creek for some distance but is lost in the area of poor outcrops south-east of Wattle Flat.

Petrography. The typical quartz-rich medium-grained arenite (grains up to 0·6 mm.) is moderately sorted with only a small percentage of matrix (Plate IX, fig. 4). The quartz grains vary from rounded to angular. Identifiable mineral inclusions are rare, though rutile, apatite and yellow tourmaline have been observed. Flakes of muscovite up to half a millimetre long are scattered through the rock. The matrix is composed of quartz silt with white mica and some chlorite. In the heavy mineral assemblage zircon is the most abundant mineral, both idiomorphic and rounded grains of comparable size are present; the rounded ones are far more abundant. Grey-green, brown and blue tourmalines have been noted; almost all show signs of rounding. Occasional grains of rutile occur. The most significant, yet least abundant mineral present in the heavy mineral assemblage is hornblende, pleochroic from yellow-green to grass-green. The finer-grained sandstones have a smaller percentage of felspar than the medium-grained ones and the sorting is better; the number of large grains is reduced with decreasing grain-size though the percentage of matrix remains much the same. The coarser sediments are more varied in their features. Micrometric analyses of some of the rocks of the formation are given in Table 1. Felspar and rock fragments become increasingly abundant in the coarser rocks. Both orthoclase and plagioclase (albite) are present; occasionally the plagioclase crystals have rows of inclusions arranged in zones indicating that there were once composition differences within the crystals. Some orthoclase is partially replaced by albite. The rock fragments are mostly finegrained, dominantly

TABLE 1

Micrometric analyses of Arenites from the Cookman Formation

	A	B	C	D
Quartz	81	60	49	30
Rock fragments	8	6	3	39
Muscovite	1	—	—	—
Chlorite grains	1	—	—	—
Felspar (Or and Ab)	1	8	2	5
Sericite-quartz matrix	10	26	46	18
Calcite	—	—	—	8

A. S 387. Maximum grain-size 0·6 mm. One mile south of type section.
B. TS 109. Maximum grain-size 1·5 mm. Type section.
C. TS 110. Maximum grain-size 3 mm. Type section.
D. TS 118. Maximum grain-size 5 mm. Type section.

fragments of the groundmasses of acid porphyritic rocks. Occasional large aggregates of quartz and felspar are present, possibly derived from granitic rocks. Rare detrital grains of microcline endorse this view. A little detrital carbonate is present both as crystalline rock fragments and as patches in the matrices of these coarser sediments.

The slates of this formation are composed of white mica, chlorite, and variable proportions of quartz silt. The abundance of mica is responsible for their pale grey colour in hand specimen.

Depositional environment and source of the sediment. East of the Wiagdon Thrust flute casts are well exposed on the bases of the overturned beds. The lobes of the flute-casts are narrower and less rounded than those in the Chesleigh Formation. Good exposures of these structures which are found on Cheshire's Creek and three miles north of it, indicate a direction of flow a little south of east. This is the opposite to that in the Chesleigh Formation. Thus, the change in direction of slope of the sea-floor implies the uplift of an area to the east. This eastern land mass incidentally, had an extremely important role in the later history of the region. The petrography of the Cookman Formation suggests that a variety of rocks were eroded off this newly exposed area, including acid volcanics (indicated by rock fragments and corroded quartzes), sediments which were quartz-rich (rounded quartzes, heavy mineral assemblage with abundant rounded zircon and less abundant rounded tourmaline), possibly granite (microcline, quartz-felspar aggregates and possibly idiomorphic zircons) and basic igneous rocks (amphibole in the heavy mineral assemblage). All of these source rocks can be accounted for in the underlying formations except for the possible granite. The material derived from the acid volcanics may have come from the erosion of the volcanics at the top of the Chesleigh Formation or the Bell's Creek Volcanics. The sediments which gave rise to the majority of the heavy mineral assemblage belonged, in all probability, to the Chesleigh Formation which would in addition, have provided the greater part of the quartz of the Cookman Formation.

The increase in the proportion of unstable rock and mineral fragments in the coarser fractions of the sediments of the Cookman Formation may be explained by considering the weathering characteristics of the suggested source rocks. The subgreywackes of the Chesleigh Formation which at this stage would be still unconsolidated, and therefore erode by disaggregation of the grains yielding small particles. The tuffs may erode by a similar process but the coarser types would give rise to the larger particles. The lavas would be eroded by the normal processes of weathering and abrasion and give rise to particles of a variety of sizes. Thus, if a sediment is composed of larger grains, then it must, of necessity, be derived from a source other than the subgreywackes of the Chesleigh Formation. The medium to fine-grained sediments of the Cookman Formation would, on the other hand, be composed dominantly of material derived from those subgreywackes. The presence of amphibole can be related to the Sofala Volcanics, mainly on the grounds that there are no other formations in the sequence known to contain amphibole. The location and age of the granite which was suggested as a possible contributor to the detritus is completely unknown.

The environment of deposition of the Cookman Formation seems to have been a deep-water one. There is some evidence of life on the sea-floor in the presence of worm tracks. The greater elongation of the flute casts in Cookman Formation suggests that the slope may have been greater in this area during the deposition of the Chesleigh Formation.

Age. No fauna has been found in this formation but fragmentary plant material was collected on the top of the high hill formed by the formation, three quarters of a mile south of the Turon River. These fragments are sometimes Y-shaped and are similar to some of the plant material found in the Silurian and Devonian in Victoria. Their age is certainly no older than early Ludlow.

Crudine Group

The Crudine Group is so called because much of the valley of Crudine Creek is cut into these sediments. There is a sharp change from the quartz-rich sediments of the Cookman Formation to the massive tuff and breccia at the base of the Crudine Group. The top of the group is the base of the very thick and massive Merrions Tuff. This is a distinctive boundary since the upper formation of the Crudine Group is one which consists of greywackes and slates and contains no tuff horizons.

The Crudine Group is several thousand feet thick and contains a variety of rock types, all typical of eugeosynclinal sedimentary associations; pyroclastics which range from coarse breccias, down to fine-grained chert-like tuffs and the normal clastic sediments which include breccias, conglomerates, sands, silts and muds all of the greywacke suite, but no chemical and organic sediments. It is difficult to distinguish between tuffaceous rocks and greywackes in some instances because the dominant source of the sediments is volcanic.

Type section. The group consists of two formations; the Turondale Formation below and the Waterbeach Formations above. The aggregate thickness of the type sections of the two formations is 3,700 feet.

a. Turondale Formation. The type section of this formation, which takes its name from the nearby village of Turondale, is on the south bank of the Turon River in Portion 46 of the Parish of Waterbeach overlying the type section of the Cookman Formation. The Turondale Formation is 2,020 feet in this section and consists of three units (Figure 2).

The lowest division of the formation, 830 feet thick, is composed almost entirely of tuffaceous material. Only 120 feet are not derived directly from volcanic sources, these are slates and fine-grained sandstones. The basal bed

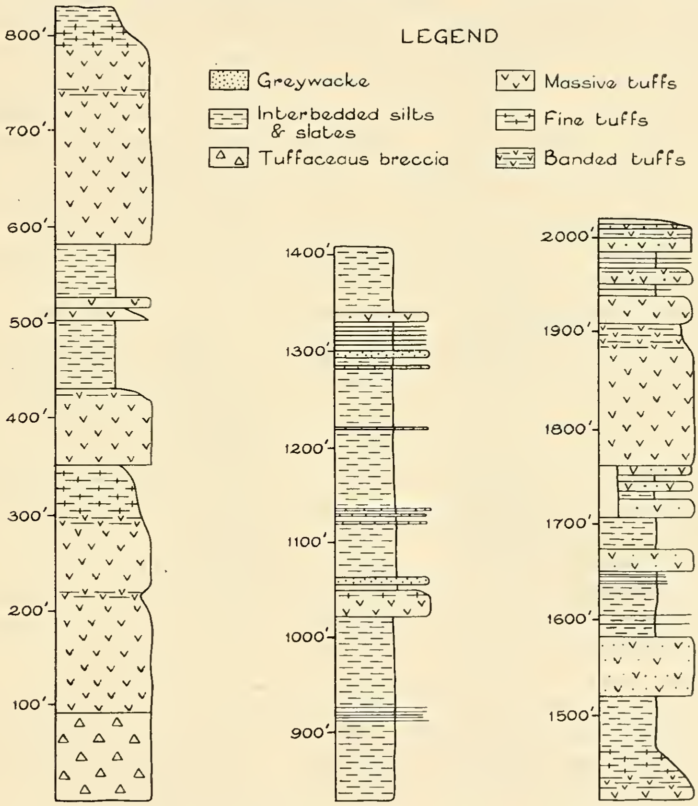

Figure 2. Type section of the Turondale Formation measured on the south bank of the Turon River in Por. 46, Parish Waterbeach. Greywacke beds less than 2 feet thick are shown as thin horizontal lines.

of the formation is a coarse conglomerate in which the matrix is at first fine-grained and makes up a large proportion of the rock but towards the top of the bed the amount of matrix decreases to about half of the rock and becomes sandy. The pebbles in the conglomerate are mainly of acid volcanic rocks with some of limestone, shale and tuff. Limestone pebbles and boulders are more abundant in the lower part of the bed. Angular shale blocks contemporaneously derived, are often very large; the largest seen had exposed dimensions of ten feet by three feet. The conglomerate passes upwards into volcanic breccia. This breccia and the succeeding tuff, which are typical of the tuffaceous sediments in the Crudine Group and the Merrions

Tuff, consist of quartz, felspar, chlorite and epidote. They are hard and massive, pale green rocks with only poorly developed bedding planes with beds of the order of tens of feet thick (Figures 2, 6, 8). Graded bedding is commonly developed over the entire thickness of the bed. The coarser phases often contain a small percentage of shale fragments and rounded felsite pebbles but most of the fragments are irregular, flattened chloritic bodies. These latter generally have inclusions of quartz and felspar, which are often embayed. Epidote and zircon are also present (Plate IX, fig. 3). The constant appearance of these bodies in sediments rich in volcanic debris in the region suggests that they have a volcanic origin. A possible explanation is that they were originally angular glassy fragments which have been subsequently converted to chlorite, possibly having passed through an intermediate stage of palagonite. This type of phenomenon has been described by Tyrrell and Peacock (1926) and Raw (1943). Other products of this process were, in all probability, subsequently converted to epidote. The very fine-grained rocks at the top of this basal bed have ill-defined bedding and a conchoidal fracture and are often translucent on the thin edges of fresh specimens. Their colour ranges from pale green through greenish-grey to dark grey. Sometimes they have spots several millimetres in diameter scattered through them in indefinite bands; these are apparently the result of local concentrations of chlorite and epidote. Above these tuffaceous sediments there are interbedded fine-grained greywackes and slates which are followed by more massive tuffaceous rocks.

The second unit, 580 feet thick, is dominantly slate and silt with bands of greywacke and a few tuffaceous beds. The tendency of these greywacke beds to occur in groups is a striking feature which is repeated at higher levels in the Waterbeach Formation and, to a lesser extent, in the Cunningham Formation. The greywacke beds differ in appearance from the tuffaceous beds below in a number of ways. The greywackes are thinner, mostly one to three feet thick, but ranging from several inches to ten feet. Shale pebbles are the most common of the larger rock fragments. Graded bedding is common but by no means universal. When present there is a gradation from greywacke to shale, whereas the tuffs, as described above, grade into cherty rocks. The slates interbedded with the greywackes are in units several inches thick, the bedding being marked by a thin silt band which occasionally shows suggestions of small-scale cross-bedding and graded bedding.

The upper part of the Turondale Formation, 610 feet thick in the type section, contains a proportion of tuffaceous material which is reminiscent of the lower part of the Turondale Formation, but the thicknesses of the beds are closer to those of the middle unit. In hand specimen, these rocks are seen to contain few rock fragments, chloritic patches are rare and so are shale fragments. There is little indication of graded bedding, where present the gradation is into shale in some beds and cherty rocks in others. In the fine to medium sand size-range some beds have alternating pale green and dark green bands, one to three inches thick, resulting from variation of the proportion of chlorite in the rock.

b. Waterbeach Formation. This formation takes its name from the parish in which the type section is defined. This section, 1,690 feet thick, is on the south bank of the Turon River in Portions 69, 74 and 49, a little over a mile west of the type section of the Turondale Formation. In the Waterbeach Formation, shaly rocks are far more abundant than sandy ones and tuffaceous rocks are absent. The base of the formation is the top of the last tuffaceous band of the Turondale Formation. There is a marked change in the characteristics of the sedimentation at this point. The greywackes are in distinct groups at 300, 800, 1,100 and 1,300 feet above the base of the formation. With the exception of shale pebble bands which occasionally occur at the bases of the thicker greywackes, conglomeratic rocks are absent from the section. A generalized stratigraphic column is given in Figure 3.

The sandy zones may represent times of greater local tectonic activity which aided erosion and hence provided coarser detritus, or alternatively, the control could be purely climatic, since periods of greater rainfall would have the same effect. Eustatic changes provide a third possible mechanism.

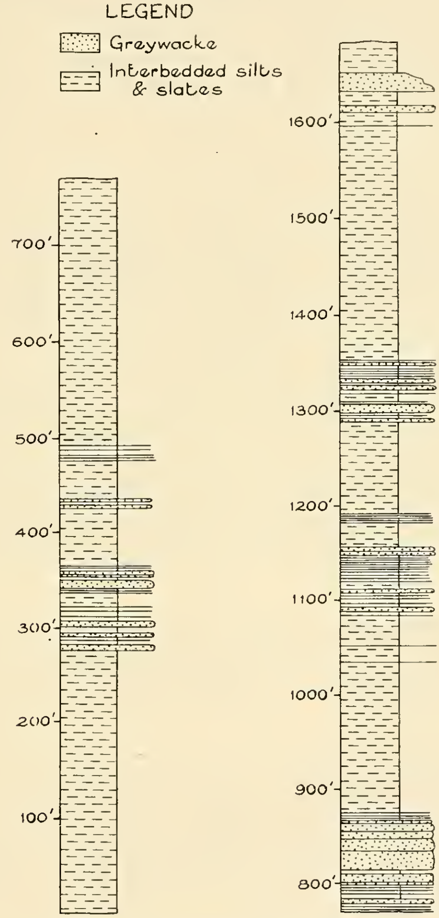

Figure 3. Type section of the Waterbeach Formation measured on the south bank of the Turon River in Portions 41, 74 and 69, Parish Waterbeach. Greywacke beds less than 2 feet thick are shown as thin horizontal lines.

It is unlikely that they represent volcanic outburts because there are no tuff horizons associated with them. Further, the petrography of the sediments indicates that material has been only partly derived from a volcanic source.

The majority of beds of greywacke and siltstones (over four inches thick) are graded-bedded. Some of the thinner silt beds are graded-bedded, passing up gradually into the overlying slate. Others form overall graded units with oscillations of grainsize within the unit. Still others have no grading, they have distinct silt bands with irregular bedding, small scale cross-bedding, or cross bedded ripple marks. In all types the silts have sharp bases frequently infilling animal trails on the top of the underlying slate unit. The silty units are generally thinner than the slate between them, the distance from the base of one silt unit to the next varying from two to six inches (Plate x, fig. 1). The thinnest beds of greywackes are the most abundant and there is a progressive decline in the frequency of occurrence of beds with increasing thickness. The thickest bed observed has a thickness of twenty-four feet. In the composite graded beds which occur occasionally, there is no parting along the junction of the coarse greywacke with the underlying fine greywacke. Occasionally, the lower unit has been dragged up into the upper unit during the deposition of the latter. Most of the graded beds maintain almost the same grain-size over the lower three quarters of their thickness then decrease gradually in grain-size in the remainder of the bed. This upper part of the bed which is normally fine greywacke or siltstone, generally has bedding planes spaced about a quarter of an inch apart. Only very infrequently is there a gradation into slate. It is possible that the beds which have no graded bedding observable in the field are beds in which the upper finer grained part of the bed has not been deposited.

The greywackes often contain angular fragments of shales which have been derived, in all probability, from contemporaneously deposited sediments by the erosive action of sediment charged turbidity currents. Normally, shale fragments included in the greywackes are four to five inches long and an inch or so thick. The largest shale fragment observed in this formation has exposed dimensions of five feet long and five inches thick. It is in a greywacke bed only three and a half feet thick. Shale fragments are the only fragments coarser than sand size found in this section of the formation.

Groove casts, flute-casts and load-casts occur on the bases of some of the greywacke beds in this formation, but their frequency is difficult to determine because the bases of the beds are infrequently exposed. Only a few slumps have been observed in this section, all of them are in the thinly bedded slate-siltstone part of the sequence. Each slump involves a foot or less of strata.

Regional variation of the Crudine Group. The Turondale Formation changes its character both across and along the strike. The most important new feature is the appearance of conglomeratic phases in the upper unit. These conglomerates are found north and south of the type section but have their greatest development three to five miles south of the Turon River where they are several hundred feet thick. In this conglomerate there is at least 60 percent of medium-grained greywacke matrix keeping the pebbles well separated (Plate x, fig. 2). The pebbles are varied in type; they include quartzite, quartz porphyry, limestone and shaly rocks. Quartzite and quartz porphyry are rounded, their size varying from less than an inch to six to eight inches along their greatest diameter. The limestone and shale fragments have been deformed along with the matrix during the folding of the succession and as a result they are flattened into lenses in the cleavage plane. By far the largest block of limestone observed measures 80 feet by 30 feet; it occurs in Portion 45 of the Parish of Waterbeach. The occurrence of this block of pure limestone containing tabulate corals, in a coarse conglomerate and its general association with graded-bedded rocks, together with the absence of any other limestone lenses and the remains of shelly fossils from the associated sediments all support the contention that it is a derived block. It is most unlikely that large pebbles and cobbles were carried by a turbidity current; it is more likely that they were carried by a mud-flow, or deposited by sliding or slumping. Further south, conglomerates are less frequent. In spite of this variation the Turondale Formation is dominated throughout by detritus of volcanic origin. The Waterbeach Formation is more constant in its characters. The only significant change in features is that to the north of the type section commencing a mile from the Turon River, a thick greywacke unit containing some conglomeratic phases is developed near the base of the formation.

The section east of the Wiagdon Thrust. The section here is thinner (2,500 feet), the tuffaceous beds are more distinct, graded-bedding does occur (Plate x, fig. 3), but is not common. The coarser beds are better sorted than in the Turon River section. Further to the east, on the eastern limb of the Jesse Syncline near the top of the group, there are fragmentary brachiopods in mudstone; this is the only locality in the Crudine Group where invertebrate fossils other than those occurring in limestone boulders have been found. One horizon of coarse conglomerate consisting of large quartz porphyry cobbles in a matrix of sand derived from similar material is exposed on Cheshire's Creek.

Direction of source of the sediments. The lithological variation described above leads one to conclude that the sediments in the eastern side of the Wiagdon Thrust are closer to their source than the rocks to the west. This view is backed up by the evidence provided by the sedimentary structures which occur in the Crudine Group. In the type section of the Waterbeach Formation between 1,100 feet and 1,350 feet above the base of the formation, there are a number of structures, flute-casts and small-scale cross-bedded current-ripples, which indicate a direction of sediment flow towards a little north of west. Three and a half miles north of the type section near the top of the Waterbeach Formation and five miles south of the type section at much the same horizon there are occurrences of small-scale cross-bedding. The former indicates a direction of flow a little south of west and the latter towards the west. Similar structures occur high in the Crudine Group east of the Wiagdon Thrust one mile west of Limekilns Public School site. At this locality, the structures indicate a slope towards the west-north-west.

Thus, at all the localities where there is any evidence of slope of the sea-floor, the general direction of slope indicated is towards the west. So the same palaeogeographic conditions must have existed during the deposition of the Crudine Group as existed at the time when the Cookman Formation was deposited.

Petrography and mode of deposition of the sediments. The sediments of the Crudine Group have few constituents. The grains of sand and silt size are: quartz, felspar, igneous rock fragments and occasional grains of calcite. These are set in a matrix of chlorite and epidote with zircon, pyrite and apatite as minor constituents. Micrometric analyses of these rocks are set out in Tables 2 and 3.

The tuffaceous rocks of the Turondale Formation differ somewhat from the greywackes of the Waterbeach Formation. The greywackes contain a larger proportion of rock fragments, a larger proportion of quartz relative to felspar and a smaller proportion of epidote in the matrix. These differences are brought out in Figure 4. Figure 5 illustrates the general resemblances between the sediments. All these arenites fall into the field of labile greywackes (Packham, 1954) and are thus distinct from the sediments of the underlying Cookman Formation which fall into the fields of subgreywackes and sublabile greywackes.

The most striking difference between the formations is in the nature of the bedding. The frequency of occurrence of greywacke beds of a given thickness in the Waterbeach Formation is roughly inversely proportional to the thickness of the bed. The tuffaceous rocks of the Turondale Formation do not show this feature at all; if anything, the thicker beds are more common than the thinner ones. This is also true of the Merrions Tuff which overlies the Waterbeach Formation. Figure 6 illustrates this difference clearly.

The problem which now arises is that of determining the mode of deposition of the tuffs. The tuffaceous rocks have normal graded-bedded sediments overlying, underlying and interbedded with them, and it is difficult to maintain that emergence has taken place so that the tuffs could be deposited in shallow water. In any case the beds lack any characters which would positively distinguish them as shallow water sediments. The Merrions Tuff extends across the strike for twenty miles and a greater distance along the strike. Such a distribution is out of keeping with the sediments being simply the result of explosive volcanic activity. It is clearly impossible for material of sand size and larger to be hurled such distances. In any case, massive beds of the thickness found could not have been deposited by such a process.

TABLE 2

Micrometric analyses of Tuffaceous Arenites from the Turondale Formation

	A	B	C	D
Quartz	20	8	12	27
Felspar	34	32	31	27
Igneous rock fragments ..	9	6	2	8
Chlorite patches	6	—	3	2
Chlorite matrix	31	54	52	36

All specimens are from the type section of the formation.
A. TS 55. 250 feet above the base of the formation.
B. TS 48. 875 feet above the base of the formation.
C. TS 45. 1,300 feet above the base of the formation.
D. TS 39. 1,470 feet above the base of the formation.

TABLE 3

Micrometric analyses of Greywackes from the Waterbeach Formation

	A	B	C	D	E	F
Quartz	15	16	28	17	13	14
Felspar	21	12	9	19	17	4
Igneous rock fragments ..	23	30	27	20	30	37
Sedimentary rock fragments	—	1	4	2	—	4
Chlorite-silt matrix ..	41	41	32	42	40	41

All specimens are from the type section of the formation.
A. TS 34. 280 feet above the base of the formation.
B. TS 38. 440 feet above the base of the formation.
C. TS 24*a*. 1,100 feet above the base of the formation.
D. TS 20. 1,350 feet above the base of the formation.
E. TS 18. 1,350 feet above the base of the formation.
F. TS 16. 1,600 feet above the base of the formation.

Textural similarity of the tuffaceous rocks and the normal greywackes (Tables 2, 3; figs 4, 5; Plate IX; figs 5, 6, 7) and the negative arguments cited in the previous paragraph lead me to the conclusion that the tuffaceous rocks were deposited by the same sort of mechanism as the greywackes, i.e., by turbidity currents or as mudflows. A terrestrial mudflow, the Osceola mudflow, described by Crandell and Waldron (1956) has a number of features resembling the tuffaceous beds of the Turondale Formation and the Merrions Tuff. The Osceola mudflow has a maximum thickness of 350 feet where it has been restricted in a narrow gorge, but the thickness decreases to less than 20 feet on the plain below. The formation is coarsely graded-bedded (the concentration of boulders being much higher at the base than the top). The proportion of clay and silt in the sample analysed by Crandell and Waldron is 39·6 percent. This accords reasonably well with the results I have obtained for the sediments of the Turondale Formation and the Merrions Tuff (Tables 2, 4) where the range is from 31 to 54 percent. Apart from the

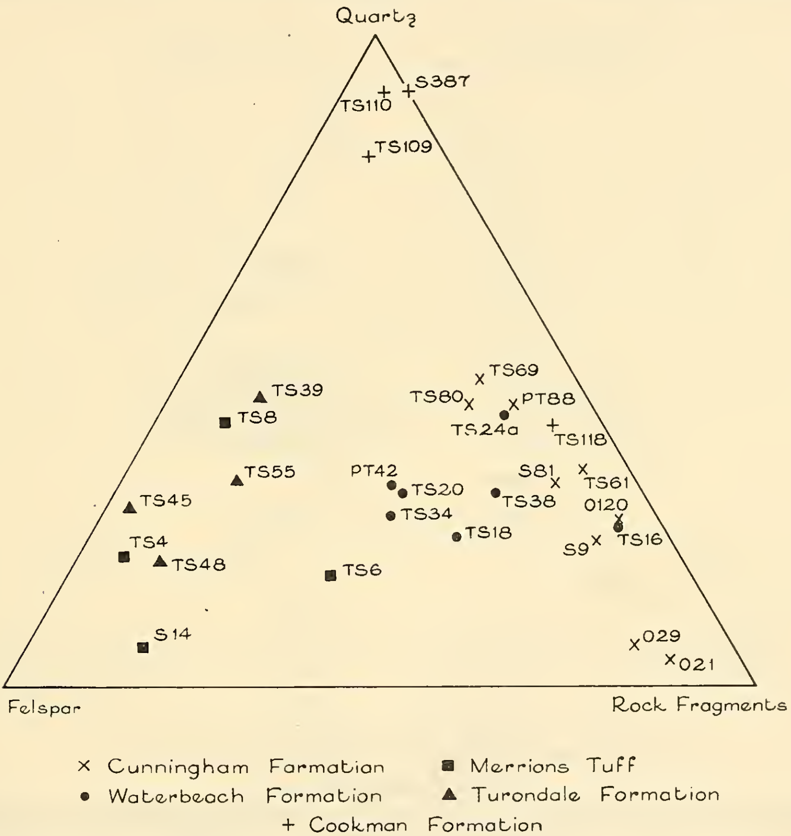

Figure 4. Plot of composition of the sand fractions of arenites listed in Tables 1–7.

greater proportion of boulders in the Osceola mudflow, its similarity to the tuffaceous rocks of the Turondale Formation and the Merrions Tuff is a close one. The lateral change of upper part of the Turondale Formation from tuffaceous rocks to greywacke conglomerate can be explained by assuming that the mudflow involved had not moved a great distance and that the variation of composition represents the influence of varied source materials.

If the tuffaceous sediments are, in fact, mudflows, then strictly speaking, it is not advisable to call such sediments "tuffs", because although they may have been intially deposited near a volcano, they were later transported to their present location. I have, however, retained the term "tuff" to distinguish these sediments from the greywackes which, though clearly derived from volcanic rocks for the most part, show no petrographic evidence that they were contemporaneous with the vulcanism.

If alternating intervals of vulcanism and quiescence are postulated, the differences between the two types of sediment may be explained. During the volcanic episodes, large amounts of detritus of sand grade were made available, hence there is a preponderance of sandy detritus over finer material. In the quiescent episode normal erosion of the terrain took place yielding large amounts of silt and clay. Weathering of felspar in this terrain was

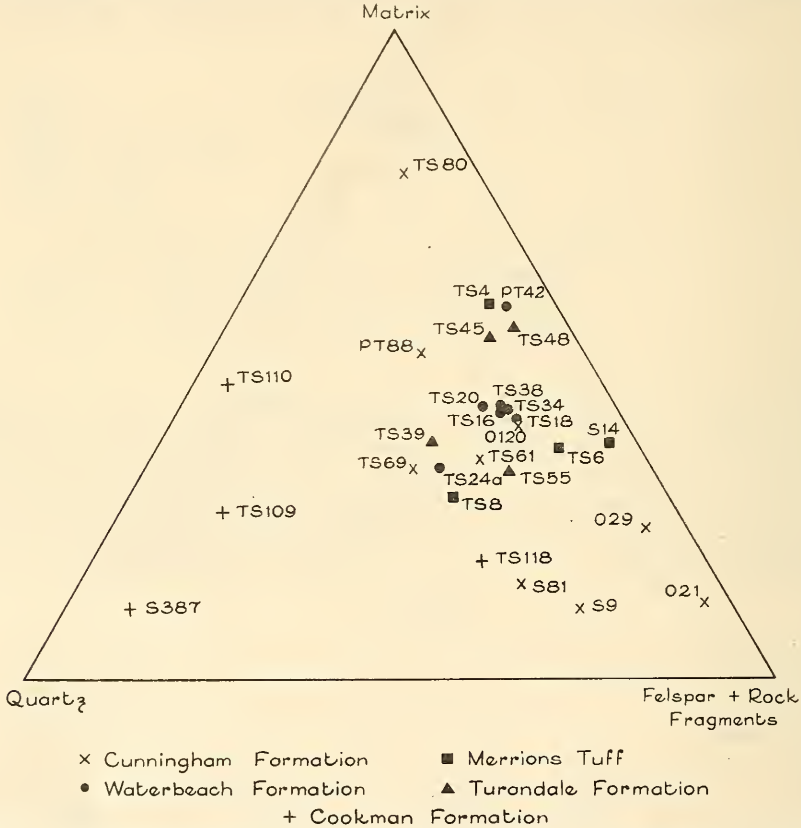

Figure 5. Plot of composition of the sand fractions of arenites listed in Tables 1–7.

probably responsible for the increase of the quartz relative to felspar in the Waterbeach Formation. Erosion of lavas extruded in the vicinity of the vents could explain the larger proportion of rock fragments.

Comparison of the frequency of occurrence of beds in this succession with those obtained by Potter and Siever (1955), for the Lower Pennsylvanian and Upper Chester sandstones (orthoquartzites) in Illinois (Figure 7), clearly brings out the difference between deep-water geosynclinal deposition and shallow-water deposition. In the geosynclinal environment the frequency of the beds in the one to four feet class is very high (70 percent) and drops rapidly, while in the shallow water environment the frequency of sandstones rises to a maximum of 20 percent in the four to eight feet class, and then falls slowly with increasing thickness.

The quartz grains in the tuffaceous sediments in the Turondale Formation are mostly angular but occasional grains have bipyramidal form, generally with slightly rounded angles. Corrosion embayments are common and are filled with fine grained material which constituted the groundmass of a lava or filled with chlorite. The largest quartz grains are two millimetres in diameter and it is these which are most frequently bipyramidal and embayed. Plagioclase (about Ab_{95}) is more abundant than orthoclase. The grains of albite are always cloudy occasionally with inclusion of epidote and almost always surrounded by epidote which has developed in the chlorite matrix. The albite grains have the same maximum grainsize as the quartz grains and, like them, sometimes have corrosion embayments filled with

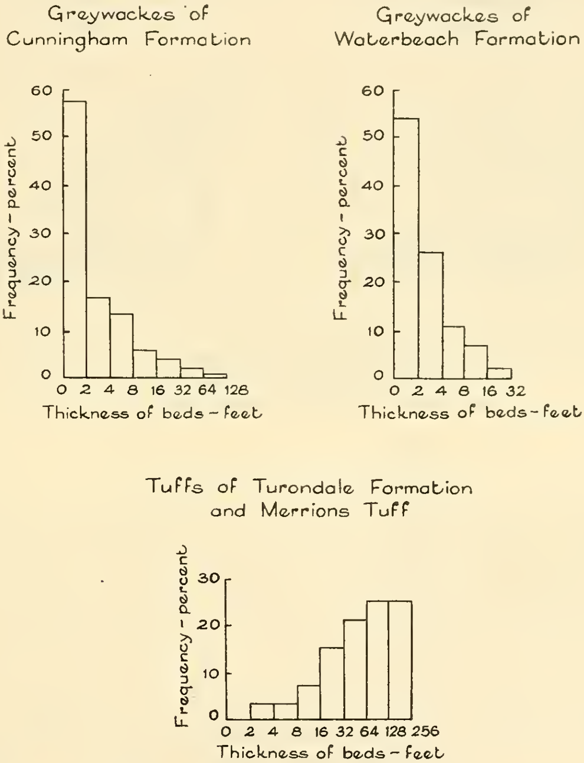

Figure 6. Frequency distribution of bed thicknesses in the type sections of the Merrions Tuff, the Cunningham and Waterbeach Formations.

chlorite. The albite grains are more often idiomorphic than the quartz grains. The morphological characteristics of the orthoclase grains are similar to those of the albite. In a number of thin-sections from the Turondale Formation the orthoclase grains have patchy replacement by albite similar to those in the upper part of the Chesleigh Formation. Glass shards, now replaced by albite, are common in some of the tuffaceous sediments; these offer positive evidence of a volcanic origin for at least some of the detritus. Very rarely, the sediments contain grains of brown amphibole. In the darker rocks, chlorite and epidote make up the entire matrix, in the lighter ones, albite is present also. Rock fragments are not common in the tuffaceous rocks, when they are present, they are acid lavas similar in mineralogy to the tuffaceous rocks.

The petrography of these tuffaceous rocks confirms the pyroclastic origin of the detritus in a number of ways; glass shards are present. Quartz and felspar grains show signs of corrosion (for some of the quartz grains this is certainly magmatic, in others it might have been post-depositional). Chlorite patches, probably derived from glassy rock fragments, are common. There is no evidence from the petrography of the sediments or the associated conglomeratic pebbles that the quartz and felspar grains were derived from a plutonic source. The small proportion of rock fragments in the sandy fraction precludes the possibility of the sediments being the result of the weathering and erosion of acid lavas and porphyries.

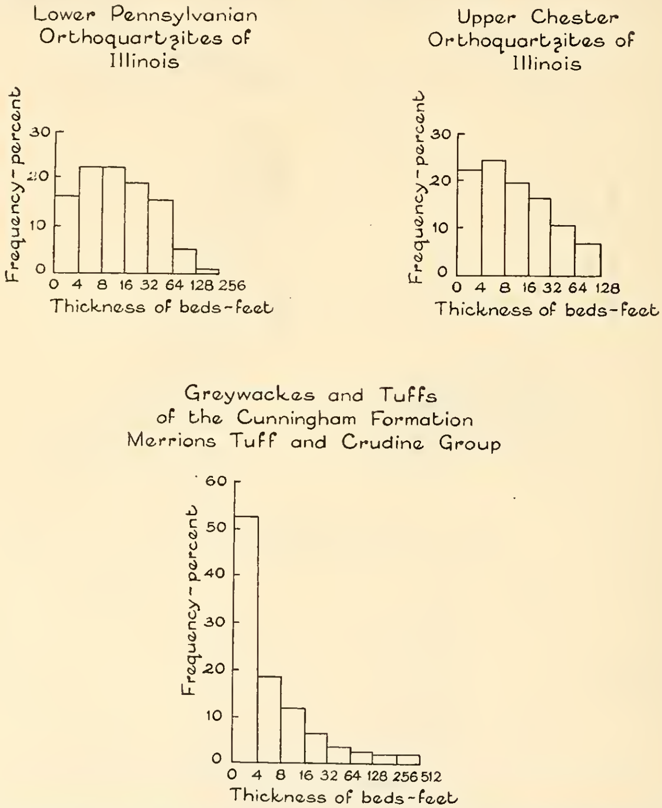

Figure 7. Frequency distribution of bed thicknesses in shallow-water sandstones in Illinois and greywackes of the Hill End Trough.

The greywackes of the Waterbeach Formation are finer-grained than the typical tuffaceous sediments of the Turondale Formation. The quartz and felspar (albite with minor orthoclase) grains are smaller and more angular in the greywackes. Igneous rock fragments are far more abundant in the greywackes than in the tuffaceous rocks. Fragments over a millimetre in diameter are normally rounded, smaller ones are angular. Shale fragments are the most abundant sedimentary rock fragments, they are frequently large and almost always angular. Limestone fragments are seen in thin-section. The matrix is of chlorite, quartz, felspar and some scattered grains of epidote. The proportion of epidote is much smaller than in the tuffaceous rocks. The proportions of the various constituents in the coarse and medium-grained greywackes do not vary greatly with grainsize in any one bed. The micrometric analyses of TS 18 and 19 (from the top and bottom respectively of a graded-bedded greywacke, Plate IX, figs 7, 6) illustrate this. The proportion of rock fragments decreases noticeably only in the finer sandstones and siltstones.

The mineralogy of the siltstones and slates throughout much of the Crudine Group is closely related to that of the coarser grained rocks associated with them. The ratio of quartz to felspar is similar and so far as can be determined in thin-section, the remainder of the rock is chlorite. The distinctive appearance of fine-grained chert-like sediments of the Turondale Formation results from their having a smaller proportion of chlorite than the slates, considerable quantities of epidote and interlocking grains.

Fauna and age. The only fossils found in the Crudine Group are ones which have been transported from their living environment. Near the top of the group approximately 5 miles north of Limekilns in Portion 107 of the Parish of Jesse a mudstone has yielded a brachiopod fauna from which Wright (1966) has identified *Dolerorthis*, sp., *Skenidioides* sp., *Isorthis* sp., *Schizophoria* sp., *Plectadonta* sp., *Notanoplia* sp., *Schelwienella* ? sp., *Eospirifer* sp., *Ivanothyris* ? sp., *Spinatrypa* sp., *Lissatrypa lenticulata* and the coral *Pleurodictyum*. In the type section of the Turondale Formation, limestone pebbles at the base of the formation contain *Tryplasma* sp., *Favosites* sp. and Pentamerid brachiopods. Near the top of the same section very poorly preserved plant remains have been found. Three miles to the south, in the upper part of the formation, limestone blocks contain *Favosites* sp. close to *F. richardsi*. The age indicated by the brachiopod fauna at the top of the group is Lower Devonian.

Merrions Tuff

This formation is extremely widespread and has proved of great value in elucidating the structure and succession of the region. The base of the formation is the base of the first tuff horizon after the greywacke succession of the Waterbeach Formation. Its top is the top of the highest tuff bed in the Hill End Trough succession where Merrions Tuff is overlain by the slates and greywackes of the Cunningham Formation. In the vicinity of Limekilns, the Merrions Tuff is overlain by shales of the lower part of the Limekilns Group. In all sections, the Merrions Tuff consists dominantly of medium sand-grade in massive beds of the order of tens of feet thick, these beds often show grading on a large scale, from breccias at the base to fine chert-like rocks at the top. Dacitic lava flows occur but make up only small proportion of the formation.

The large-scale graded-bedded units commence with a basal breccia which contains large chloritic bodies (Plate X, fig. 4) of the type described in the account of the Turondale Formation, sometimes angular blocks of shale and less frequently, rounded pebbles of quartz porphyries and limestone. The matrix is composed of coarse sand-grade mineral fragments (albite, orthoclase, quartz with interstitial chlorite and epidote). This is succeeded by progressively finer detritus with an alternation of light and dark bands several inches thick, the colour banding apparently resulting from variation of the chlorite content. Sometimes just below the banded rocks there is a zone which has a mottled appearance. This too, results from an uneven distribution of chlorite through the rock. The banded rocks pass upwards into finer tuffs, poorly bedded, light in colour and often with indefinite slump structures. These rocks have a chert-like appearance and are frequently spotted. They have been described in the discussion of the Turondale Formation.

Type section. The type section (Figure 8) of this formation is along the south bank of the Turon River in Portion 41 of the Parish of Waterbeach, overlying the type section of the Waterbeach Formation. The name of the

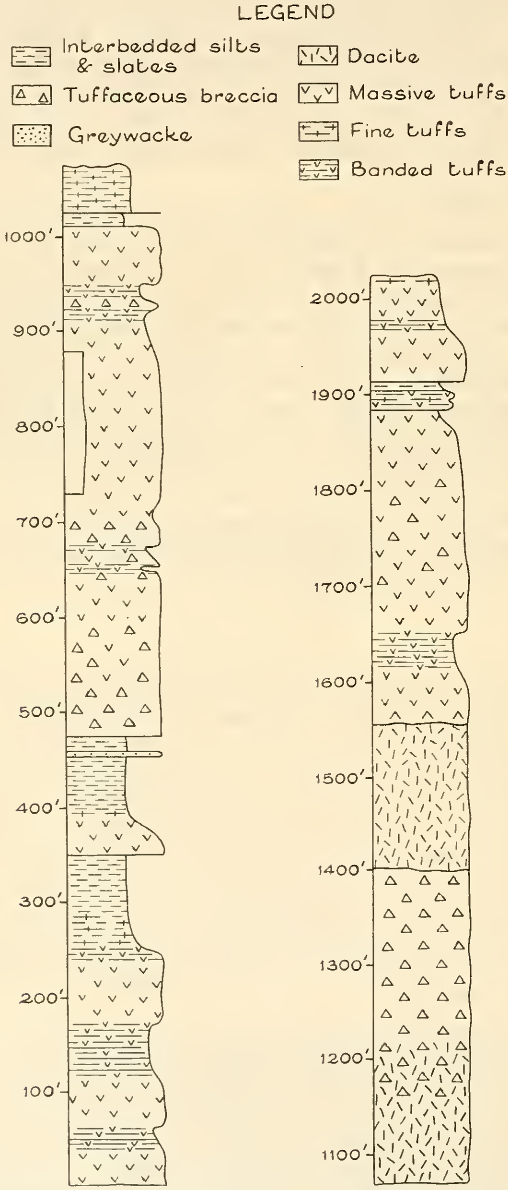

Figure 8. Type section of the Merrions Tuff measured on the south bank of the Turon River in Portion 31, Parish Waterbeach.

formation is derived from Merrions Trig. Station south of the type section on a high ridge formed by the outcrop of the formation. The measured thickness of the type section is 2,020 feet, this order of thickness is typical of the formation. The formation can be divided into four units in this section. The lowest 475 feet of the formation contains four thick tuff beds. The lower two commence with coarse tuff and pass upwards into banded tuff which is followed abruptly by coarse tuff. The upper two tuffaceous beds pass into indurated shaly rocks with characters similar to those of the Waterbeach Formation. Interbedded with the fine-grained sediments at about 470 feet above the base of the formation there are two greywacke beds with all the characters of the typical greywackes of the Waterbeach Formation except that they contain a larger proportion of quartz and felspar and a correspondingly smaller proportion of rock fragments.

The next 600 feet of the formation is almost entirely coarse tuff. Two exceptionally thick beds occur. The lower one is over 150 feet thick and the upper one is over 200 feet thick. Shale blocks included in the base of the lower one are up to two feet across while the upper one has large chloritic blocks at its base.

Five hundred feet of rock containing tuff and lava flows then follow. At the base lava rests with an irregular contact against cherty rocks at the top of the underlying unit. This lava passes upwards into brecciated lava—possibly a flow breccia then into a breccia more closely resembling the coarser phases of the tuff. This is followed by another lava flow.

The remaining 460 feet of the formation commences with a very coarse breccia (Plate x, fig. 4) which grades up into finer sediments. The next bed is over two hundred feet thick, it has some fluctuations in grainsize but becomes finer in the upper part. Above is an alternation of tuff and cherty rock followed by seven feet of sediments with the bedding features of the shaly rocks of the Waterbeach Formation. The formation concludes with a hundred foot unit which grades from breccia at the base into cherty rocks at the top.

Regional distribution and variation. South of the Turon River the formation remains much the same as the type section, but to the north there is lateral change in the lowest unit of the formation, where an increase in the proportion of intercalated strata takes place and some of the tuffs pass into conglomerates with cobbles of felsitic rocks. The lavas, too, in the north differ somewhat in hand specimen from those in the type section; vesicular types are common, the cavities being filled with epidote, prehnite and calcite.

The general lithological identity and bedding characteristics of the formation are maintained in the Limekilns area on the east side of the Wiagdon Thrust where the formation is of the order of 1,500 feet thick. There is a felsitic lava flow at the base to the north-east of Limekilns. Overlying the tuff is a black shale (the Rosedale Shale) which is poorly bedded and contains no tuffaceous material. The junction with the Merrions tuff is sharp.

Petrography. Apart from minor differences, the sediments (Plate III, fig. 1) of this formation are the same as the tuffaceous rocks of the Turondale Formation. Amphibole is still rare but is more common than in the Turondale Formation. It has the following optical properties: Z = slightly greenish mid-brown; X = very light brown; $Z \wedge C$ about 17°; moderately large 2V. Orthoclase, often partly sericitized, is common only in coarser tuffaceous rocks; the mineral has more albite patches than in the type section of the Turondale Formation. Comparison of the micrometric analyses of sediments from the two formations (Tables 2, 4) and their positions on Figures 4 and 5 bring out this similarity. The mode of deposition of the tuffaceous rocks is discussed above.

The lavas associated with the Merrions Tuff are altered dacites; they are tough dark grey to greenish grey rocks. The phenocrysts are mainly of felspar (1·0 mm.), very rich in soda (about Ab_{95}) and frequently corroded. Quartz phenocrysts are not abundant but are always corroded. In one thin-section a pale green non-pleochroic pyroxene was found. Amphibole similar to that in the tuffs is occasionally present. The groundmass of the lavas is composed of plagioclase laths (0·1 mm. long), granular quartz, grains of epidote and wisps of chlorite. The degree of alteration in these rocks is considerable; in most slides chlorite and epidote pseudomorphs after amphiboles are common.

Table 4

Micrometric analyses of Tuffaceous Arenites from the Merrions Tuff

	A	B	C	D
Quartz	3	27	10	8
Felspar	51	35	30	31
Igneous rock fragments ..	6	—	19	3
Sedimentary rock fragments ..	—	—	5	—
Chloritic patches	4	7	—	3
Chloritic matrix	36	31	36	55

All specimens are from the type section of the formation.

A. TS 14. 50 feet above the base of the formation.
B. TS 8. 350 feet above the base of the formation.
C. TS 6. 850 feet above the base of the formation.
D. TS 4. 1,030 feet above the base of the formation.

Cunningham Formation

This formation is named after the parish in which the type section occurs. The formation consists of slates, siltstones, greywackes and conglomerates. Lavas and tuffs are absent. Some of the greywacke beds are thicker than those of the Waterbeach Formation but at the same time considerably thinner than typical beds of the Merrions Tuff.

Type section. This is along the banks of the Turon River in Portion 138 of the Parish of Cunningham, conformably overlying the type section of the Merrions Tuff. The stratigraphic column is given in Figure 9. The type section which is a little over 2,800 feet has been measured to the top of the highest bed exposed.

The proportion of sandy material and the grainsize of the coarser beds is greater in this section, than in the type section of the Waterbeach Formation. These two features have associated with them, an increase in thickness of the coarsest beds and a less distinct alternation of sequences of fine sediments with groups of greywacke beds than in the type sections of the Waterbeach Formation and the middle part of the Turondale Formation. In the Cunningham Formation type section, the coarser beds are more abundant between 300 and 900 feet, 1,050 and 1,150 feet, 1,250 and 1,550 feet, 1,750 and 1,850 feet, and 2,130 and 2,350 feet above the base. The coarsest greywackes in this formation are in thick beds—the thickest is 70 feet, one is 60 feet thick and there are a number over 30 feet. This contrasts with the type section of the Waterbeach Formation on which the thickest bed is 20 feet. On the basis of number per hundred feet of section, thinner greywacke beds are more abundant in the Cunningham Formation than in the Waterbeach Formation. Most beds up to four or five feet thick are graded-bedded but the thicker beds display irregular fluctuations of grainsize. The siltstones and slates are similar to those in the Waterbeach Formation.

At two places in the type section, namely 1,450 and 2,150 feet above the base, beds quite different in texture from the greywackes occur; the first is 18 feet thick and the second is 50 feet in thickness. These are massive, dark grey in colour, consisting dominantly of clay and silt size material (see Table 5, Plate XI, fig. 2) but with a small proportion of coarser material.

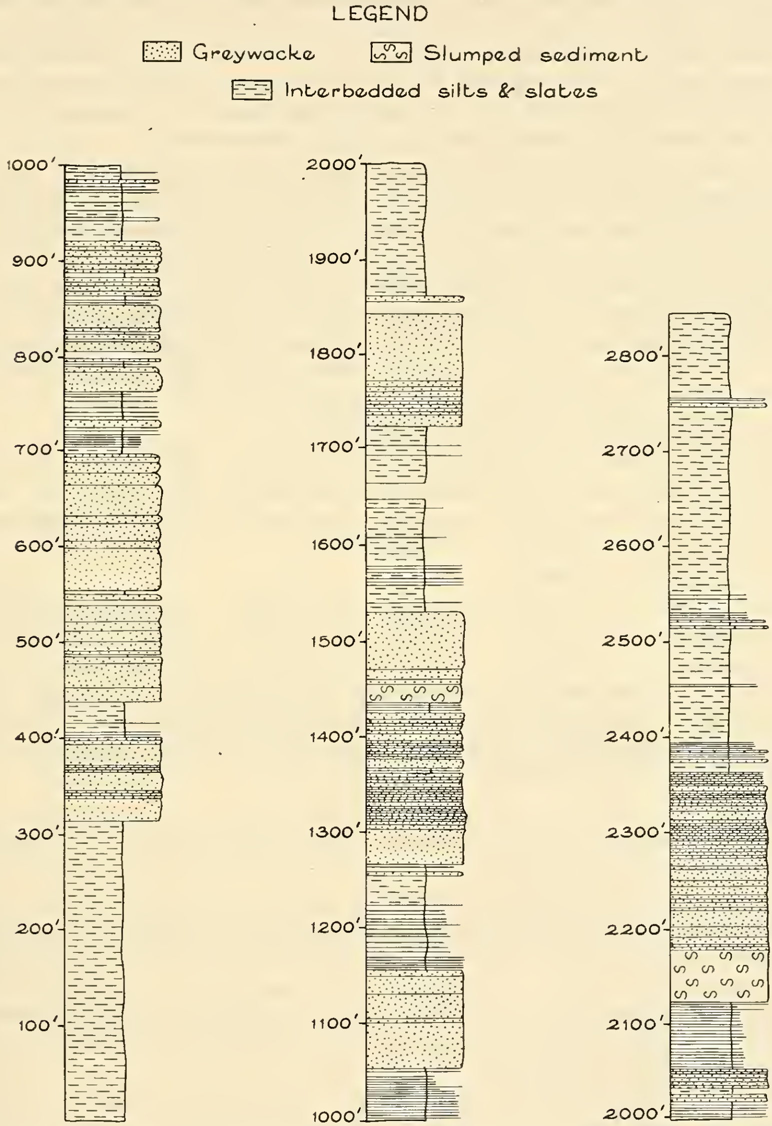

Figure 9. Type section of the Cunningham Formation measured on the south bank of the Turon River, Portions 41, 50, Parish Waterbeach. Greywacke beds less than 2 feet thick are shown as thin horizontal lines.

In the lower one the largest pebbles are 2 to 3 inches in diameter, whilst in the upper one the maximum size is 6 inches. The lower bed contains deformed blocks of shale up to two feet in diameter in a matrix which has folded banding. One brachiopod fragment was found in this bed. The upper bed is composed dominantly of a finer banded phase with about 80 percent clay and silt and a second phase which contains an appreciable proportion of sand sized grains. The boundaries between the two phases are sharp but very irregular (Plate x, fig. 6). Both are boulder bearing. The best explanation of the origin of these two beds is that they are mudflow or highly mobile slump deposits. The sporadic banding of the rock, the irregular distribution of boulders through the bed, the incomplete mixing of the fine-grained and sandy phases of the upper bed and the contortion of the banding of the lower bed are all in agreement with this conclusion. The symmetry of the contortions, incidentally, suggests that the direction of flow was from east to west. The inclusion of the brachiopod in the lower bed suggests that the flow was initiated in a fairly shallow-water environment.

The observations made regarding the origin of the alternation slate-rich and greywacke-rich zones (p. 29) apply equally to the Cunningham Formation. A volcanic origin can be definitely ruled out because there is no indication of vulcanism during the deposition of the Cunningham Formation. It is interesting to note that the upper mudflow horizon occurs at the base of a greywacke cycle which is over 200 feet thick. This commences with thickly bedded greywackes but the thickness of the beds gradually diminishes upwards. This may have been caused by an uplift in the source area or fall in sea level, erosion gradually obliterating the effects of the change and the supply of sandy debris gradually diminishing.

Regional variation. The formation is confined to the western margin of the area under discussion but some variation in the proportion of various lithologies occurs. Greywackes with an abundance of shale fragments are more common to the south and to the west there is a rapid decrease in the abundance of coarse sediment.

Source direction of the sediments. Flute-casts and small-scale cross-bedding occurring at intervals throughout the type section and the flow-deformed banding in the lower mudflow horizon all indicate a direction of sediment flow towards the west. Small-scale cross-bedding indicating a similar direction of flow occurs near the base of the formation at Gimlet Creek (four and a half miles due south of the type section) and again at several points in the section exposed by Winburndale Rivulet.

Thus the same direction of slope of the sea-floor was maintained from the time of deposition of the Cookman Formation until the deposition of the Cunningham Formation.

Petrography and sedimentation. Because of the higher proportion of shale fragments the appearance of the Cunningham Formation greywackes differs from that of the Waterbeach Formation greywackes. The coarser phases of the Cunningham greywackes may contain up to fifty percent of shale fragments. The grey colour of the Cunningham Formation greywackes contrasts with the greenish grey of those of the Crudine Group which contain a higher proportion of epidote.

Micrometric analyses of some of the sediments of the Cunningham Formation are given in Table 5 and are plotted in Figures 4, 5. The proportion of felspar is significantly lower in the Cunningham Formation than in the Waterbeach Formation. The thin-section characteristics of the various types of detrital minerals and rock fragments are identical in both formations. There are fragments of porphyritic acid igneous rocks, limestone, shale and quartzite. A single pebble of granite found in a conglomerate phase of the Cunningham Formation does not necessarily indicate any change in the source area because a few granite pebbles have been found in the Waterbeach Formation in the Hill End area. The siltstones and slates of the Cunningham

Formation are poorly sorted; they differ from those of the Waterbeach Formation only in that they contain a higher percentage of detrital quartz. The percentage of matrix in the Cunningham greywackes is more variable and often considerably lower than in the Waterbeach greywackes (Plate xi, figs 4, 5), and the beds are often considerably thicker; only two percent of the greywacke beds in the type section of the Waterbeach Formation are over 16 feet thick, while 10 percent of those of the Cunningham Formation type section exceed this value. If the initial slope from the shallow-water environment into the trough in which the Cunningham Formation was deposited, was steeper than for the Waterbeach Formation, and if, the trough had a flatter floor, then I think the differences could be explained. The steeper slope would allow flowing grain layers (Sanders, 1965) or turbidity currents with a smaller amount of fine material to flow; the sediments found in the type section of the Cunningham Formation may have been deposited at the foot of such a slope as a submarine fan. The rarity of slumps in this section offers evidence against deposition on the slope. Had the slope continued further to the west, it would be expected that the coarse sediments would be common for a considerable distance in this direction. This is not the case.

TABLE 5

Micrometric analyses of Greywackes from the Cunningham Formation in the Sofala district

	A	B	C	D	E
Quartz	31	22	10	20	27
Felspar	9	4	3	9	9
White mica	—	—	7	—	—
Igneous rock fragments	25	32 }	3	57	48
Sedimentary rock fragments	2	8 }		3	2
Matrix	33	34	77	11	14

A. TS 69. Type section, 330 feet above the base of the formation.
B. TS 61. Type section, 1,380 feet above the base of the formation.
C. TS 80. Type section, 2,150 feet above the base of the formation.
D. S 9. Sofala-Hill End road, $\frac{1}{2}$ mile west of the eastern boundary of the formation.
E. S 89. Sofala-Hill End road, $\frac{3}{4}$ mile west of the eastern boundary of the formation.

Fauna. Apart from a brachiopod fragment in one of the mudflow horizons, no fossils have been found in this formation other than those occurring in limestone pebbles in the coarser sediments. Tabulate corals are the most abundant. The forms found are favositids, one is doubtfully *Emmonsia* sp., the others are *Favosites* sp. One rugose coral, possibly an Acanthophyllid has been found.

Age. The best evidence for the age of this formation comes from its correlation with the Devonian Limekilns Group (see below). The Cunningham Formation can be traced westwards to the Euchareena area where it passes laterally into shallow-water sediments containing Lower Devonian fossils.

LIMEKILNS GROUP

This group consists of three formations which overlie the Merrions Tuff in the vicinity of Limekilns, five miles south-east of Wattle Flat. These three formations were first described by Hawkins (1953). In ascending order, the formations are the Rosedale Shale, the Jesse Limestone and the Limekiln Creek Shale. There is no indication of contemporaneous vulcanism within the group though it is overlain and underlain by thick pyroclastic formations, the Winburn Tuff and the Merrions Tuff respectively.

The age of the limestone in this group has been known to be Devonian for many years but the limestone was not mapped stratigraphically until it was studied by Hawkins (1953). The Limekilns Group has an important place in the interpretation of the palaeogeography of the region since it contains neritic benthonic organisms in their living environment and is of the same age as the Cunningham Formation which is a typical geosynclinal deep-water succession. The evidence for this correlation rests on a number of different lines of approach. First, they both overlie the Merrions Tuff conformably. Then the lithologies are comparable, in that they are both non-volcanic; this is not a common feature in the succession. Again, sedimentary structures in the Cunningham Formation in the Turon River section show that the sediment has been transported from east to west, indicating the existence of an area with a shallow water environment somewhere to the east.

The thickness of the Limekilns Group in the Limekilns area is of the order of 2,500 feet. This may be an overestimate because faults are difficult to detect in the Rosedale Shale and the Limekiln Creek Shale.

a. *Rosedale Shale.* This formation which has been named after a property at Limekilns, has its type section (as designated by Hawkins, 1953) in Pender's Creek in Portions 1, 16 and 63 of the Parish of Jesse. A sharp contact with the Merrions Tuff marks the lower boundary. The shale is dark grey to black, well jointed and fisile but with macroscopic bedding planes every six to eight inches. Pyrite is common. The shale is composed of quartz and felspar silt set in a fine-grained matrix of chlorite and sericite. Chlorite is the more abundant. Fossils are rare, there are only occasional linguloid brachiopods and poorly preserved plant remains. The thickness quoted by Hawkins for this formation is 700 feet.

b. *Jesse Limestone.* This formation conformably overlies the Rosedale Shale. The outcrops to the east of Limekilns are thickly bedded limestones and breccias, while those to the west are dominantly calcarenites 50–100 feet thick, in which individual beds can be traced for distances of at least a mile. Hawkins (1953) designated the section of the clastic facies exposed in Diamond Creek as the type section. The base and top of the formation in the type section are respectively the base of the first calcarenite bed and the top of the highest one.

The limestone is highly fossiliferous, though the massive limestone is less abundantly so than the detrital facies to the west. *Syringaxon* ? sp., *Phillipsastraea currani*, *Hexagonaria tunkanlingensis*, *Disphyllum* sp., *Dendrostella* sp., *Spongophyllum* sp., *Acanthophyllum mansefieldensis*, *Grypophyllum* sp., *Lyrielasma* sp., *Tryplasma* sp., *Pseudamplexus* sp., *Plasmophyllum australe*, *Calceola* sp. and *Receptaculites australis* have been identified by Wright (1966). Brachiopods, stromatoporoids, tabulate corals, fish plates and conodonts are also known from the formation. Preliminary identifications of the conodont fauna are: *Bellodella devonica*, *B. resima*, *Hindeodella prescilla*, *Lonchidina* sp., *Neoprioniodus excavatus*, *Neoprioniodus* sp., *Ozarkodina denckmanni*, *Paltodus acostatus*, *P. unicostatus*, *P. valgus*, *Polygnathus linguiformis foveolata*, *Spathognathodus exiguus*, *Synprioniodina* sp. and *Trichonodella* sp. The assemblage is apparently a late Lower Devonian one (Emsian).

Towards the north, along the Limekilns-Wattle Flat road, the limestone thins very considerably and the formation is represented by a few impure calcareous arenites. These contain, apart from detrital carbonate, porphyritic acid igneous rock fragments as the most abundant constituent with quartz grains less abundant and felspar least abundant. This the same order of abundance as the various types of detritus in the greywackes of the Cunningham Formation.

c. *Limekiln Creek Shale.* This formation was also defined by Hawkins (1953). It has its type section in Cheshire's Creek in Portion 253 and the eastern part of Portion 127 of the Parish of Wiagdon. The thickness of the formation given by Hawkins is 1,500 feet. It overlies the Diamond Creek Limestone and underlies the Winburn Tuff. The lithology and fossil content are similar to those of the Rosedale Shale.

Winburn Tuff

The formation has its type section in Cheshire's Creek, in Portion 127 of the Parish of Wiagdon (Hawkins, 1953). The formation is named after a parish which has Cheshire's Creek as its boundary and so the south bank of the creek in the type section is actually south of Limekilns, in the Parish of Winburn. The dips of the underlying shales are frequently discordant with the boundary of the tuff which may lie unconformably on the Limekilns Group.

The formation occurs in the core of a synclinal structure truncated to the west by a thrust fault. The section is thus incomplete but over 2,000 feet of it is preserved. Lithologically, the formation is very similar to the Merrions Tuff. The beds are thick and the greatest part of the formation is composed of tuff of coarse sand size. The remainder is composed of finer tuffaceous sediments.

No indication of vulcanism has been found within the Cunningham Formation and this is taken as an indication that the Cunningham Formation pre-dates the Winburn Tuff and so may be equated with the Limekilns Group. There is no formation to the west with which the Winburn Tuff can be correlated.

There is a general textural and mineralogical resemblance between the Winburn Tuff and the Merrions Tuff. The rocks are poorly sorted and composed of white and pink felspar, quartz, epidote and chlorite; rock fragments are not abundant. Orthoclase is the dominant felspar, it is often partly replaced by albite in patches about a tenth of a millimetre long or less commonly, by narrow veins along the cleavage. The detrital plagioclase in the rock is albite. Epidote is less abundant than in the Merrions Tuff.

The Stratigraphy of the Hill End District

There have been three previous geological maps of the Hill End region, each covering an area of about 100 square miles surrounding the town. The first was by Pittman (1881); his map showed that the town, and thus the mineralized zone, lay on the crest of an anticline, but he made no attempt to subdivide the succession. The second map was produced by Harper (1918) who, because he misinterpreted some sedimentary structures in the succession, considered that an unconformity was present. The third study was by Jopling (1950) who reaffirmed the original simple concept of Pittman, but again there was no serious attempt to divide the sequence into units, since the purpose of Jopling's study was to investigate the gold mineralization. The anticline on which the town of Hill End is situated gives the most complete section in the central part of the region. The sequence of formations from the Chesleigh Formation to the Cunningham Formation, described in the Sofala district can also be recognized in the Hill End area. The geological map accompanying (Plate IV), incorporates the Hill End area.

Chesleigh Formation

The lowest part of the section consists of massive subgreywackes, with tuffs and thin beds of slates at the base. Above this, massive tuffaceous rocks appear which have sorting akin to that of greywackes; these tuffaceous rocks are reminiscent of those in the Turondale Formation of the Crudine Group, but their association with massive subgreywackes is one unknown in that formation to the east. The exposed thickness of the formation in the Hill End area is about 1,700 feet, in all probability representing the upper part of the Chesleigh Formation which, in the type area, contains volcanic material.

Unfortunately, it has not been possible to obtain any evidence of the direction of transportation of the sediments in the Chesleigh Formation outcropping in the Hill End area; the direction of source of the Chesleigh Formation in the Sofala-Wattle Flat area is from the west or a little to the south of west. The Hill End area would be expected to be a little closer to the source area; this seems to be reflected in the lithology of the sediments. The non-volcanic sediments are more felspathic; a notable addition is the presence of a small amount of microcline. There is also a suggestion of coarsening of grainsize, indicated by a greater abundance of shale blocks in the subgreywackes. Volcanic material is also more abundant here than in the type section, again suggesting a closer proximity to the source region.

The outcrop in the Hill End district, is confined to the axial region of the Hill End Anticline, and occupies a strip, less than two miles in width, commencing two miles north of the town of Hill End and extending south for 16 miles. The outcrop is cut off to the north and the south by the gentle plunge of the fold.

Cookman Formation

In the Hill end Anticline, the Chesleigh Formation is flanked by the Cookman Formation with an outcrop width of just under half a mile on both limbs. Good cliff sections exist where the Cookman Formation crosses the Turon and Macquarie Rivers. The Cookman Formation also outcrops to the east of the Hill End Anticline in the axial regions of three small anticlines along the Macquarie River upstream from its junction with the Winburndale Rivulet. Only the upper part of the formation is exposed in each case. The thickness of the Cookman Formation in the Hill End area is about 2,300 feet, *i.e.*, considerably thicker than in the type section (1,500 feet). The coarser sediments like those of the type section, are almost all quartz-rich with a few percent of argillaceous matrix; they occur in beds mostly one to two feet thick. Unlike the type section, graded-bedding is well developed although the size range is rather more restricted here. These features suggest a location for the Hill End sections of the Cookman Formation further from the source of the sediments. The indications in the Sofala area were that the sea-floor sloped to the west during deposition of the Cookman Formation in contrast with the general easterly slope at the time of deposition of the Chesleigh Formation. In the Turon River cliff section of the formation exposed on the eastern side of the Hill End Anticline slipped load-casts, small-scale cross-bedding and slumps are occasionally found and these indicate a westerly slope on the seafloor.

In hand specimen, the subgreywackes of this formation differ in appearance from those in the Sofala area. This difference results from the greater degree of metamorphism in the Hill End area. Thus, instead of the rock being moderately indurated and quartzite-like with individual grains fairly distinct, it has been converted to a very hard, brittle, somewhat translucent and hornfels-like rock in which the grains are entirely interlocking. Under the microscope it is difficult to determine the nature of the original texture.

Crudine Group

Both the Turondale and the Waterbeach Formation can be traced into this area and maintain many of the characteristics found in their type sections.

Turondale Formation

This overlies the Cookman Formation in the Hill End Anticline and outcrops over the whole length of the anticline in the area mapped. Although it does not appear in any of the anticlines to the west of the Hill End Anticline it does outcrop extensively east of it, in the anticlinal structure west of the junction of the Macquarie River and the Winburndale Rivulet. This outcrop has a width of three miles on the southern border of the map, interrupted only by three small inliers of the Cookman Formation. To the north this anticlinal structure plunges north so that the Turondale Formation disappears under higher formations.

The thickness of the formation seems to be fairly constant in the region and of the same order as the thickness measured in the Turon River section at Hill End, that is, 2,200 feet (in the type section it is 2,000 feet). The lithology likewise is similar—mainly tuffaceous rocks and greywackes. The beds are thick but for the most part the coarse rocks characteristic of the lowest part of the formation in the type section are not present. This means that the junction of the Turondale Formation with Cookman Formation is not such a distinct one as in the Sofala area but it can be recognized by an increase in the thickness of beds, the presence of some beds of coarse sand size and the presence of acid tuffs and most important, the change from dominantly quartz detritus to lithic and felspathic debris. Although there has been a reduction of the maximum grainsize of the sediments in this formation in the Hill End area, the abundance of coarse-grained sediments is far greater here than in the Waterbeach Formation. Some of the thicker beds of the Turondale Formation contain blocks of shale—one of these observed in Washing Gully of Hill End is ten feet long. Indications of slumping movements are often seen in these beds. The tuffaceous rocks range from coarse sand-size through to fine cherty types.

A porphyry, twenty to thirty chains wide in outcrop, occurs within the Turondale Formation, at the same stratigraphic level, on both sides of the Hill End Anticline. Even where its contacts are exposed there is no clear evidence that the porphyry is intrusive and, further, it has obviously been involved in the folding movements since it is strongly deformed. It may be a flow. An inclusion of granite with a rounded outline, measuring approximately two feet by one foot is exposed in the porphyry in the bed of Washing Gully a mile and a quarter west of Hill End. The inclusion shows some signs of disruption for small groups of crystals, evidently derived from the granite, are seen separated from the inclusion by a narrow vein of the porphyry. There is no indication of the development of any kind of reaction rim around the inclusion.

The evidence of the direction of slope of the sea-floor is in harmony with what has been found in the Sofala area. The general indication is that the slope was from east to west, which means that the Hill End section was further from the shore. This accords with the lithological data such as the absence of the coarsest tuffs and the increase in proportion of greywacke. The data indicating the slope are a slump structure in tuffaceous sediments on the Macquarie River three miles south-east of the junction of the Turon and Macquarie Rivers and the occurrence of cross-bedded ripple marks near the base of the formation 300 yards west of the same river junction. Small-scale cross-bedding exposed on the bank of the Macquarie River, 15 miles south of Hill End on the western limb of the Hill End Anticline, indicates an easterly downward slope of the sea-floor. Thus, the axis of the trough in which the Turondale Formation was deposited lay in the vicinity of the Hill End Anticline.

Waterbeach Formation

This formation outcrops extensively in the Hill End area. It appears on both limbs of the Hill End Anticline and, on the eastern side towards the south of the area, can be traced around several folds to the junction of Winburndale Rivulet and the Macquarie River. About 6 miles west of the Hill End Anticline the Waterbeach Formation outcrops in the axial region of the Ulmarrah Anticline (Figure 1).

The appearance of the Waterbeach Formation in most sections is closely similar to that in the type section with the notable exception of the inlier in the Ulmarrah Anticline described below. The usual features are: an absence of tuffs, a preponderance of slates over greywackes, and well developed graded-bedding, especially in the slates. This graded-bedding is better developed than in the type section. The same tendency characterizes the Cunningham Formation in this area.

In a number of places in the section of the Waterbeach Formation exposed on the western limb of the Hill End Anticline, flute casts and small-scale cross-bedding indicate a down-slope of the sea-floor from east to west. Hence, the same direction of slope persisted from Sofala at least as far west as this section.

The thickness of the Waterbeach Formation south of Hill End on the Turon River is 2,000 feet, 350 feet thicker than the type section.

In the Ulmarrah Anticline immediately underlying the Merrions Tuff there is over 900 but less than 1,500 feet of extremely deformed sediment. This material is part of a huge slump, the base of which is not exposed. The sediment in the deformed zone is coarse greywacke and slate, which have been mutually involved in the slip. The greywacke (Plate xi, fig. 7) is not a normal one; it contains a proportion of matrix much larger than is normal and the sorting is poorer (cf. Table 6). In the field it is also unusual, for included in it are blocks of a great variety of rocks, the largest and commonest being shale. Blocks 15 feet across are common. Other inclusions are not only far less frequent, but of considerably smaller size, being for the most part rounded boulders up to 2 feet in diameter. Rock types represented are: quartz-felspar porphyries, biotite-granite, limestone, dacitic tuff, quartzite and quartz. In places the boulder-bearing material and deformed slates are overlain by little-deformed graded-bedded slates but elsewhere the slate is clearly injected by irregular masses of the greywacke (Plate x, fig 7); these injection movements clearly pre-date the regional cleavage. These relationships may be the result of first, the slumping of the coarse material into a position of temporary stability, then deposition of graded-bedded shales on top followed by a later slip of both the first slump and its cover. This process may have been repeated a number of times. Some of the contact between the two phases might represent a slide-plane within the whole slump mass. As it has not been possible to recognize any systematic arrangement of folds within the slumped material, no direct evidence of the direction of source of the slump is available.

By far the best exposures of the slump mass are in the gorge of Pyramul Creek on the northern edge of the area mapped. To the south, outcrops in the axial region of the anticline are poor but the occurrence of poorly sorted greywackes and boulder beds, suggests that the slump extends for at least six miles along the axis of the anticline. Further south the Waterbeach Formation is concealed by the overlying Merrions Tuff. To the east, in the Hill End Anticline, there is no certain indication of the slump, despite good exposures. The only possible disturbed area is on the west limb of the anticline on Pyramul Creek where some of the interbedded slates and greywackes are rather more folded than usual; this folding, however, might be tectonic. Although the evidence for the direction of origin of the slump mass is negative, it suggests that the slump was derived from the west since, if it had come from the east the effect certainly would be clearly noticeable in the exposures in the Hill End Anticline. Again, if the slump had moved from the east to the west the distance of movement would have to be very considerable since boulder-bearing horizons are rare in the Waterbeach Formation within the area mapped. Since sediments in the Waterbeach Formation, on the western limb of the Hill End Anticline, indicate a westerly slope of the sea-floor, the axis of the trough in which the formation was deposited must have lain in the vicinity of the Ulmarrah Anticline or slightly to the east of it.

TABLE 6

Micrometric analysis of Greywacke Matrix of Ulmarrah Slump

	Pt
Quartz	12·2
Felspar	12·7
White mica	2·8
Rock fragments	13·8
Matrix	58·2

Locality : Axis of Ulmarrah Anticline in Pyramul Creek.

Another boulder-bearing greywacke, this time a very thin bed, by comparison with the slump described above (the thickness of sediment involved is only of the order of tens of feet), outcrops in the core of an anticline some twelve miles south-east of the Ulmarrah Slump but is east of the Hill End Anticline and so is unrelated to the large slump.

MERRIONS TUFF

In the Hill End Area, this formation maintains the character of its type area at Sofala better than the underlying units. North of the Turon River it outcrops on both the eastern and western limbs of the Hill End Anticline but to the south occurs only along the western limb. On the eastern limb the Merrions Tuff outcrops over a considerable area between the Macquarie and Turon Rivers due to the northerly plunge of several folds of moderate amplitude west of the Hill End Anticline. East of these structures the formation again strikes southwards along the western side of the synclinal structure continuing south from Sally's Flat. To the west of the Hill End Anticline the tuff outcrops on both limbs of the Ulmarrah Anticline as far south as the Macquarie River. The unit again occurs in a southerly-plunging anticline on the northern edge of the area mapped, between the Hill End Anticline and the Ulmarrah Anticline. The Merrions Tuff in the Ulmarrah Anticline is the most westerly outcrop of the formation in the region under discussion. The area east of the Hill End Anticline is structurally different from other areas in which the tuff outcrops for here it is tightly folded into sharp crests and troughs whereas elsewhere it behaves in a more competent fashion.

Lithological and bedding characteristics similar to those of the formation in the type section are maintained in the Hill End area, where the thickness is over 2,000 feet on the eastern limb of the Hill End Anticline. To the west of Hill End the formation contains less coarse material and the section is thinner (about 1,000 feet at Ulmarrah). Altered dacitic lavas are present in nearly all exposed sections and generally they occur at, or near, the base of the formation. The lavas sometimes have columnar jointing and, as a result of the regional deformation in which they have been involved, the north-south dimension of the columns is generally one and a half times the east-west dimension.

The lithological continuity of the Merrions Tuff and the decrease in thickness to the west are such that it must have been derived from the east. A shift to the west of the axis of the trough must be postulated to account for the extension of the sediment as far west as the western limb of the Ulmarrah Anticline. During the time of deposition of the underlying Waterbeach Formation the axis lay in the vicinity of the Ulmarrah Anticline.

Cunningham Formation

The type section of the Cunningham Formation which is described above is on the western side of a synclinal structure running through Sally's Flat. South of the Turon River the formation is restricted by the complex anticlinal structure occurring between the river and the Hill End Anticline but northwards the formation extends across to the anticline. West of the Hill End Anticline the Cunningham Formation outcrops over a very large area in a broad synclinal structure (the Ophir Syncline, Figure 1) roughly ten miles wide. The continuous outcrop is broken only by the lower rocks in the Ulmarrah Anticline and the small structure between it and the Hill End Anticline. The Cunningham Formation can be traced west to Euchareena; the outcrops there are discussed below.

The thickness of the Cunningham Formation in the Ophir Syncline is of the order of 12,000 feet. This is far greater than the thickness of the type section (2,800 feet). But it is not certain whether the formation has thickened to the west since there is no formation overlying the type section of the Cunningham Formation.

The lithology of the Cunningham Formation in the Hill End area differs from that of the type section principally in the proportions of the various rock types. Fine-grained sediments are far more common here and conglomeratic greywackes are very rare. To the west of Hill End greywackes are rare except near the base of the formation and there they are rich in felspar apparently derived from tuffaceous rocks. Between 5,000 and 6,000 feet above the base of the formation, a few thin graded-bedded and slumped bands of arenite and rudite composed largely of calcareous debris, outcrop on the banks of the Macquarie River between Curragurra Creek and Pyramul Creek. The detritus was apparently derived from the west where the Cunningham Formation passes into limy sediments. The formation here consists almost entirely of slate. Individual bands of silt are not common. Almost all of the silty material occurs at the base of graded slaty beds. These graded units are thicker than those described as occuring in the type section of the Waterbeach Formation. The general order of thickness of beds is six inches in the Cunningham Formation in this area.

The location of the axis of the trough in which the formation was deposited seems to have been in the vicinity of the Hill End Anticline. This is suggested by two lines of evidence. First, the shale-pebble conglomerates which are so characteristic of the formation in the eastern part of the region only extend as far west as the eastern limb of the Hill End Anticline. Secondly, there are frequent slump structures west of the Hill End Anticline; these make their appearance on the western limb of the anticline and are found commonly in most sections to the west of it. Good examples of these slump structures are exposed in Tambaroora Creek upstream from Washing Gully and at a number of places along the Macquarie River between Tambaroora Creek and Lewis Ponds Creek west of the axis of the Hill End Anticline. No direct evidence of the direction of movement of the sediment has been obtained by an examination of the structures because the amount of movement has almost completely destroyed the bedding. The deformed material, largely of clay and silt size, is often cut by veins of silty material probably deposited while water was being squeezed from the plastic mass after its final deposition. The indications of graded-bedding and other structures, which remain suggest that the initial deposition of the sediment was in deep water. The fine-grained nature of the sediments involved in these slumps and the absence of similar structures on the eastern side of the Hill End Anticline suggest an easterly slope of the sea-floor as far as the Hill End Anticline. Convolute bedding is common locally in very fine silts just west of the Ulmarrah Anticline and near the junction of Lewis Ponds Creek and the Macquarie River.

The Stratigraphy of the Euchareena District

The Devonian limestones and some of their associated sediments in the valleys of Nubrigyn and Boduldura Creeks, west of Euchareena and Stuart Town have been mapped and petrographically examined by Wolf (1965). Apart from this, there have been only two significant contributions to the geology of the area, the original mapping by Carne and Jones (1919) of the limestones studied by Wolf and the reconnaissance mapping of the western margin of the area by Joplin and others (1952).

Oakdale Formation

The oldest rocks in the Euchareena district are andesitic volcanics, representing a southern extension of the Oakdale Formation from the Mumbil District (Strusz, 1960). The Ordovician age of the volcanics has been established by the finding of graptolites at four localities. The northernmost is in Portion 10, Parish of Nubrigyn. Sherrard (1954) states that the graptolites here are: *Climacograptus bicornis*, *Climacograptus scharenbergi*, *Orthograptus* cf. *apiculatus* and *Lasiograptus* ? *harknessi*. Two miles to the south on the boundary of Portions 4 and 48 of the same parish there are fragments of *Dicellograptus* sp. Further south again on the Bell River just east of the Silurian Nandillyan Limestone (Joplin and others, 1952), I have found *Orthograptus* cf. *apiculatus* and *Glossograptus hinksii*. The fourth locality is 2¼ miles west of Mullion Creek Railway Station, by the side of the Belgravia Road. The forms identified are *Orthograptus apiculatus* and *Climacograptus* sp.

These andesitic volcanics occupy the same position in the succession as the Sofala Volcanics and are of comparable age. There is some difference in the general appearance of the rocks in the two areas. The andesitic volcanics in the western area are far less indurated than the Sofala volcanics and the interbedded fine-grained rocks are shales rather than chert.

An important section occurs on the eastern margin of this formation in the northern-western corner of the area mapped, in a gully flowing into Nubrigyn Creek through Portion 10 of the Parish of Nubrigyn. The section is as follows:

The lowest rocks exposed are andesites, overlying these is a thin limestone followed by shales with the fauna containing *Climacograptus bicornis* mentioned above; this in turn is followed by marls and a second thin limestone containing a fauna of tabulate corals overlain by a thick succession of arenites consisting of material derived from andesites and finally a Silurian limestone at the base of the Mumbil Formation, containing Pentamerids, *Tryplasma* sp., and a rugose coral close to *Phaulactis shearsbyi*. The exposed section below the Mumbil Formation is about a thousand feet thick.

The fauna of the lowest limestone in this sequence is highly significant; it includes halysitid corals, *Syringopora* sp., *Heliolites* sp., and *Multisolenia* sp. A comparable fauna has been found in the Oakdale Formation, about thirteen miles to the north (Strusz, 1960). The graptolite assemblage has been placed by Sherrard (1954) in the zone she calls the Zone of *Climacograptus peltifer* but there is no clear reason why it should be placed in that zone. The fauna is compatible with the assemblage two zones higher in what she calls the Zone of *Orthograptus calcaratus* and *Plegmatograptus nebula*. Thus the field observations indicate that the *Halysites* fauna extends down into the Upper Ordovician at least as far as the last-mentioned zone.

Mullions Range Volcanics

In the Mullions Range this formation occupies the axial region of an anticline plunging to the north. Unfortunately no older formations outcrop in the structure so that it has not been possible to determine the thickness of the formation in the Mullions Range. The formation outcrops to the west of the Mullions Range as a gradually narrowing strip, running slightly west of north. It has been traced as far north as Eadvale.

There are at least 5,000 feet of the volcanics exposed in the Mullions Range, but in the well-exposed section along Kerr's Creek, chosen as the type section, the volcanics are only 1,500 feet thick. The thickness of the formation diminishes rapidly towards the north. In the type section there is a dacite flow at the base, followed by breccias of similar composition and then another dacite flow. On top of this are more clastic sediments—tuffs and coarse sandstones. The section ends with a flow of banded rhyolite. The changes in thickness within the formation seem to be an original feature, since there is no local indication of an erosional break at the top. A volcanic centre in the vicinity of the Mullions Range, may account for the distribution of the formation. The Mullions Range Volcanics rest on the Ordovician andesitic rocks described above (Oakdale Formation).

The volcanics are almost exclusively dacites and rhyolites. The coarsest rocks are porphyry-like types; these grade in grain-size to types containing only a very small percentage of minute phenocrysts. The fine-grained types are difficult to identify positively in the field because of their similarity to the inter-bedded, indurated clastic rocks. The fine-grained lavas are pale greenish-grey when fresh and only very rarely banded, so very few dips and strikes can be obtained within the outcrop of the formation. The phenocrysts in the lavas are orthoclase, plagioclase (albite) and quartz. Felspar and quartz are roughly equal in abundance. The groundmass is composed of interlocking grains of quartz and felspar, with only minor amounts of biotite (X = pale yellow-brown and Z = very dark brown), mostly altered to chlorite. Epidote is common, occurring as grains in the groundmass.

The clastic sediments in the formation are all highly indurated. They range from fine silts to coarse sandstones and are composed of material derived from the lavas. Glass shards are common in some of the tuffs.

The age of this formation will be discussed after the description of the overlying formations.

Mumbil Formation

The Mumbil Formation originally described by Strusz (1960) in the Mumbil district, conformably overlies the Mullions Range Volcanics. It has been mapped from the northern extremity of the area, south to Kerr's Creek, around the margin of the Mullions Range in the Parish of Trudgett and then down the eastern side of the range to Frederick's Valley Creek. In the northern part of the area the formation rests directly on rocks older than the Mullions Range Volcanics.

The section in Frederick's Valley Creek is 1,200 feet thick consisting of grey and greenish-grey slate, commonly containing large pyrite cubes, and is almost devoid of bedding. The cleavage developed in the type section is not typical of the formation as a whole. To the west, the cleavage gradually diminishes in intensity, from Nubrigyn Creek to Kerr's Creek it is virtually absent. The formation is non-volcanic and composed of fine-grained sediments. The base of the formation, where it rests on the Mullions Range Volcanics is taken as the top of the last lava or tuff band of the volcanics. At the northern extremity of the area the formation rests on the Oakdale Formation. The upper boundary is the base of the first tuff band of the Bay Formation in the vicinity of the Mullions Range. In the Nubrigyn Creek area where the thickness is only about 300 feet, the base is the lowest tuff band or andesite flow of the Cuga Burga Volcanics. Just to the west of Kerr's Creek where neither the Mullions Range Volcanics nor the Cuga Burga Volcanics is present, the mapping of the Mumbil Formation is very difficult since it is overlain by the Cunningham Formation which contains few sandy bands here. The top of the Mumbil Formation has been taken in this area as the place in the sequence where the greenish colour of the claystones gives way to the grey shales and siltstone bands of the Cunningham Formation.

A number of limestone lenses have been recognized within the Mumbil Formation as shown on the map; they are probably equivalent to the Narragal Limestone (Strusz, 1960). The fauna of the northern-most one includes *Tryplasma* sp., *Phaulactis shearsbyi* and pentamerid brachiopods.

Bay Formation

The Bay Formation outcrops around the northern and eastern flanks of the Mullions Range. Outcrop commences near Kerr's Creek Railway Station passing around the northern end of the Mullions Range, along the eastern side through Bay Trigonometrical Station (after which the formation is named), and then south to Frederick's Valley Creek. The Bay Formation overlies the Mumbil Formation and underlies the Cunningham Formation but there is apparently an erosional break between the Bay Formation and the overlying Cunningham Formation. West of Kerr's Creek the Bay Formation is absent and the Cunningham Formation rests on the Mumbil Formation. The type section of the Bay Formation is exposed in Curragurra Creek at the northern extremity of the outcrop of the formation. The thickness in this section is approximately 400 feet, from here the thickness increases steadily along the eastern margin of the Mullions Range reaching about 1,500 feet at Frederick's Valley Creek. The proportions of the various lithologies making up the formation change throughout its outcrop. The type section is representative of the northern and more westerly part of the formation. It consists dominantly of tuffs of dacitic composition lithologically very similar to the variety of types found in the Merrions Tuff, ranging from coarse-grained crystal tuffs with chlorite-rich patches, to fine-grained chert-like types with a conchoidal fracture. A small proportion of siltstones and slates are present. By contrast, sections exposed to the south-east contain a higher proportion of slates and silts. In Frederick's Valley Creek, tuffs are less abundant than slates and silts and some greywackes are present. The top of the formation is taken as the top of the last tuff bed. It is overlain by greywackes, conglomerates and slates of the Cunningham Formation.

Cuga Burga Volcanics

Like the Bay Formation, the Cuga Burga Volcanics conformably overlie the Mumbil Formation. The volcanics occur only in the north-western corner of the area, extending south as far as the head of Weandre Creek. The volcanics have been traced intermittently into the Mumbil District whence they were first described (Strusz, 1960). The best exposed section in the Euchareena district is seen in the vicinity of Eadvale, in the east-west gully in Portion 58 of the Parish of Nubrigyn. The exposure there consists of about 1,000 feet of andesite flows which exhibit pillow structures in places, overlain by about 500 feet of interbedded shales and tuffaceous rocks. These latter are similar to the tuffs of the Bay Formation, containing abundant felspar, some quartz and chlorite. The beds of tuff are thin, of the order of one to three feet thick. The top of the formation is the uppermost bed of tuff.

Cunningham and "Nubrigyn" Formations

The Cunningham Formation is by far the most extensive stratigraphic unit in the Euchareena area, outcropping from Nubrigyn Creek to the Macquarie River. Limestones, impure calcarenites and conglomerates interdigitate with the western margin of the outcrop of the Cunningham Formation. The limestones were mapped by Carne and Jones (1919) who gave them the name of the Nubrigyn (limestone) belt. All the limestone lenses were collectively called the Nubrigyn Limestone by Packham (1958). Wolf (1965) modified this term by including the clastic calcareous and lithic sediments as well as the limestones in the Nubrigyn Formation. The southern and eastern limits of the formation have not been defined closely, so at present it seems best to use the term "Nubrigyn Formation" provisionally until its stratigraphic and geographic limits are established. The approximate limits of the rocks of "Nubrigyn Formation" lithology are shown on the regional geological map.

The basal beds of the Cunningham-"Nubrigyn" sequence along the western margin of the outcrop are shales which are overlain by interbedded calcareous labile sandstones, polymictic conglomerates and shales, containing limestone lenses which Wolf (1965) regards as algal bioherms. The limestone lenses occur abundantly over about six square miles mainly south of Boduldura Creek but extend south over about nine miles. Wolf (1965) divided the sequence above the basal shale into four units in the Boduldura Creek area. The lowest consists of well-bedded impure calcareous sandstones, calcarenite, shale and large algal bioherms. The second is not so well bedded, the algal bioherms are smaller and more frequent, local areas of andesite occur (? flow remnants) and there are limestone breccias developed around some of the limestone pods. The third unit contains abundant volcanic detritus and further ? flow remnants. Current bedding is common in the arenites. The highest part of the exposed section is an algal bioherm. The thickness of these strata preserved in this area is of the order of 1,700 feet.

Much of the calcareous material in the "Nubrigyn Formation" contains obscure organic structures which Wolf (1965) regards as algal. From the better preserved material Johnson (1964) has described the following algae: *Hedstroemia australe*, *Garwoodia primitiva*, *Litanaia robusta*, *L. cracens*, *Abacella deliculata*, *Lancicula wolfi*, *Uva* sp., *Litopora spatiosa*, *Girvanella* sp. aff., *Girvanella ducii*, *Rothpletzella devonicum* and *Renalcis devonicus*. Johnson also records the presence of the encrusting foram *Wetherdella*. Many other fossil groups are present, tabulate and rugose corals are common, stromatoporoids, brachiopods and conodonts have been found. The coral fauna recorded by Strusz (1968) is *Acanthophyllum* (*Neostringophyllum*) *implicatum*, *Calceola* sp., *Eridophyllum immersum*, *Hexagonaria approximans cribellum*, *Pseudochonophyllum pseudohelianthoides* and *Xystriphyllum dunstani*. *Pseudamplexus princeps*, *Tryplasma* spp. and *Receptaculites* sp. are also present. A number of conodonts have been isolated from beds in the lower part of the formation 0·6 miles north-north west of the junction of Boduldura and Nubrigyn Creeks. The forms present include *Spathognathodus linearis*, *S. inclinatus wurmi*, *S.* cf. *steinhornensis*, *Icriodus pesavus*, *Ozarkodina* sp. cf. *O. jaegeri*, *O. media*, *O. denckmanni*, *Trichonodella* sp., *Neoprioniodus* sp., *Hindeodella* sp. and *Panderodus unicostatus*. The age of the formation is Lower Devonian, its precise position is discussed later in this paper.

The other material in these sediments is igneous and metamorphic; fragments of andesites, basalts, dolerite, fine-grained acid volcanic rocks, quartzite and granite are all present. The first two were probably derived from the underlying Oakdale Formation, the Cuga Burga Volcanics or possible contemporaneous flows. The dolerite fragments are very altered and very little can be determined of their original petrography. Dolerites are known to intrude Ordovician and Silurian rocks to the south-west in the Cargo-Cudal district (Stevens, 1950), to the north in the Wellington district (Basnett and Colditz, 1946), and closer at hand to the north in the Mumbil district (Strusz, 1960); intrusions of this type are a likely source for the dolerite fragments in this formation. The acid volcanic fragments bear a strong resemblance to the rocks of the Mullions Range Volcanics, part of which could have been exposed at the time. The fragments in question bear very little resemblance to the Silurian Canowindra Porphyry (Stevens, 1950; Ryall, 1965) which outcrops to the west but could be compared with the early Devonian lavas of the same region, i.e., the Bull's Camp Volcanics (Packham and Stevens, 1955), the Duladerry Rhyolite (Stevens, 1954) and similar rocks in the Cumnock area (Joplin and others, 1952). The last mentioned is only 12 miles west of Nubrigyn Creek. The quartzite and granite pebbles are more difficult to account for, they apparently came from further afield.

The arenites and conglomerates in the vicinity of Nubrigyn Creek are well sorted (see Table 7) and occasionally cross-bedded. The arenites have a carbonate cement (Plate XI, fig. 6) or a small proportion of chlorite matrix (Plate XI, fig. 8). Individual beds are lenticular. These features, as well as their intimate association with the algal limestones, point to deposition in a shallow water environment.

To the east of the calcareous facies of the "Nubrigyn Formation" both arenites and conglomerates are rare and almost all of the succession consists of slates and silts. Patches of conglomerate have been found in three localities, viz., two and a half miles west of Euchareena, by the side of the Molong road; in the first railway cutting to the north of Euchareena Railway Station; on the road one and a half miles west of Store Creek Railway Platform. The first and second localities are important since the conglomerates contain fossils: *Acanthophyllum* sp. and *Calceola* sp. at the first, and *Acanthophyllum* sp. and *Syringopora flaccida* at the second locality. In view of the association of these conglomerates with fine-grained sediments and their occurrence in small masses it seems likely that they are slide deposits.

South of Nubrigyn Creek, sandy beds are not common in the lower part of the Cunningham Formation. In the vicinity of Kerr's Creek, the coarsest beds are laminated siltstone to very fine sandstone bands. To the east of this latter area, where the Cunningham Formation is in contact with the Bay Formation, some of the basal beds of the Cunningham Formation in the vicinity of the Mullions Range are conglomeratic, containing pebbles of acid lavas and quartzite. These conglomerates differ from those occurring to the north-west in the vicinity of the Nubrigyn Limestone in that they contain a larger proportion of matrix. The arenites and the conglomerates of the southern area are of the greywacke suite (Plate XI, fig. 5, Table 7) in contrast to those of the labile sandstone suite in the north-west.

TABLE 7

Micrometric analyses of arenites from the Cunningham Formation in the Euchareena district

	A	B	C	D
Quartz	21·2	13·8	5·0	3·6
Felspar	5·1	5·4	10·0	8·8
Igneous rock fragments ..	13·6	36·1	61·5	73·4
Sedimentary rock fragments ..	9·5	5·0	14·7	5·4
Matrix	50·6	39·7	8·1	8·8

A. PT 88. Greywacke, Curragurra Creek, 3 miles east of Euchareena.
B. O 120. Greywacke at base of Cunningham Formation, Curragurra Creek, 4 miles south-east of Euchareena.
C. O 21. Labile sandstone, from "Nubrigyn Formation", 4 miles west of Euchareena.
D. O 29. Labile sandstone, from "Nubrigyn Formation", 7½ miles north-west of Euchareena.

East of Store Creek and Euchareena, arenites are extremely rare. In the entire section exposed in Curragurra Creek there are only two or three beds of greywacke (the micrometric analysis of one of these is given in Table 7). Graded-bedding is common only east of the railway line. The silts have occasional bands of small-scale cross-bedding and convolute bedding. Unfortunately most of these structures have been observed in loose blocks on the sides of hills and it has not been possible to use them as indicators of the direction of slope of the sea-floor.

A magnificent slump structure is exposed in the narrow gorge of Curragurra Creek, four miles east of Euchareena. The structure is not so spectacular as the Ulmarrah Slump in the Hill End district because here the rock types involved are limited to interbedded silts and slates and the mass is only about 200 feet thick. The original bedding is still preserved, normally in folds with axial planes close to the regional dip. In places the sandy beds are reduced to contorted fragments in a shaly matrix; some of these fragments of beds are ten or so feet long (Plate X, fig. 8). Examination of the folds in this slump indicate that the anticlines, recognizable by the presence of graded bedding in the silts, have their crests facing east, suggesting that the slump has moved towards the east and hence the sea-floor must have sloped downwards in that direction. This accords with the facies change of the formation towards shallow-water to the west and establishes the existence of a trough (the Hill End Trough) of sedimentation to the east. The eastern margin of this trough has been shown to lie to the east of the Wiagdon Thrust where shallow water sediments are again developed in the Limekilns area.

It is not known whether this slump is a local phenomenon or whether it forms an extensive slump sheet. The suggestion was made in the description of slump structures in the Hill End area (p. 66) that they originated to the west of Hill End and moved eastwards to their present locations. They could have originated anywhere on the easterly-sloping sea-floor and thus it may not be possible to trace them back to the western limb of the Ophir Syncline. The degree to which bedding has been destroyed in the slumps just to the west of Hill End indicates that they have moved considerably further than the slump in Curragurra Creek.

Ages of Formations in the Euchareena District

The Oakdale and Mumbil Formations of the Euchareena district represent the southern extension of the two oldest formations of the Mumbil district (see Table 8). Their occurrence at Mumbil and their fauna have been described by Strusz (1960, 1961). Although Upper Ordovician graptolites

Table 8
Regional correlation table

	Quarry Ck.-Borenore	Mumbil	Eadvale	Mullions Range	Hill End Sofala	Limekilns
Givetian						Winburn Tuff
Eifelian		Cunningham Formation	Cunningham Formation	Cunningham Formation	Cunningham Formation	? / Limekilns Ck. Sh.
Emsian	?	Cunningham Formation	Nubrigyn "Fm."			Jesse Limestone / Rosedale Shale
Siegenian	Garra Fm. / Sandstn. & congl.	Tolga Calcarenite			Merrions Tuff	Merrions Tuff
Gedinnian	Bull's Camp Volcs. / Wallace	Cuga Burga Volcanics	Cuga Burga Volcanics	Bay Fm.	Crudine Group	Crudine Group
Ludlovian	Shale / Panuara "Fm."	Barnby Hills Shale	Mumbil Formation	Mumbil Formation	Cookman Formation / Chesleigh Formation	Cookman Formation / Chesleigh Formation
Wenlockian		Narragal Ls. / Mullions Ra. Volcanics	Mullions Ra. Volcanics	Mullions Ra. Volcanics	Bell's Creek Volcanics	?
Llandoverian	Panuara "Fm."		?		Tanwarra Shale / ?	Tanwarra Shale
Upper Ordovician	Malachi's Hill Formation	Oakdale Formation	Oakdale Formation	Oakdale Formation	Sofala Volcanics	Sofala Volcanics

occur in the Oakdale Formation at Mumbil, the highest beds, which contain limestone lenses, are Upper Ordovician or Lower Silurian on the evidence of their contained coral fauna. Strusz (1960) considered the overlying Mumbil Formation to range from "the topmost Llandoverian through most or all of the Wenlockian". Beds which Strusz regarded as basal beds of the Narragal Limestone (the lower member of the Mumbil Formation) contain some distinctive forms, including: *Palaeophyllum* sp., *Multisolenia tortuosa* and *Acanthohalysites australis*. Forms occuring in the main part of the limestone include: *Phaulactis shearsbyi* and *Entelophyllum latum*. *Monograptus bohemicus* (Lower Ludlow) occurs low in the overlying Barnby Hills Shale, which is the upper member of the Mumbil Formation. Dr. Strusz and I recently revisited the area and found that the limestones which he regarded as basal beds of the Narragal Limestone are separated from it by a thin succession of acid to intermediate volcanics, and thus the "basal" limestones are either part of or rest directly on the Oakdale Formation. The fauna is the same as that in the Oakdale Formation, and has little in common with the Narragal Limestone. There is no clear evidence then, that the Narragal Limestone extends far below the top of the Wenlock. In the vicinity of Euchareena, the Mullions Range Volcanics occur between the Oakdale and Mumbil Formations. These volcanics can be correlated with the acid to intermediate volcanics which underlie the Mumbil Formation at Mumbil (Table 8).

Further afield at Quarry Creek, 24 miles south-south-west of Euchareena, the Silurian sequence can be dated with some accuracy by means of the contained graptolite faunas (Packham, 1968). Beds at Quarry Creek, containing *Monograptus bohemicus* and therefore equivalent to the lower part of the Barnby Hills Shale are underlain by shales containing Upper Wenlock graptolites (principally *M. testis*). These are in turn underlain by cross-bedded sandstones, derived from acid volcanics. Below these sandstones are shales and fine quartzitic sandstones containing Upper Llandovery graptolites (*M. marri* is the most common). There is therefore a break in sedimentation between the Upper Llandovery and the Upper Wenlock, the result of an uplift called the Quarry Creek Phase of the Benambran Orogeny by Packham (1967*a*). Limestone (the Quarry Creek Limestone) underlies the Upper Llandovery sandstones and shales and overlies Upper Ordovician andesitic volcanics which can be correlated with the Oakdale Formation. The clastic succession with limestone bands at the top of what has been mapped as the Oakdale Formation near Nubrigyn Creek might contain Llandovery beds and be separate from the volcanics.

In view of the break in sedimentation recognized at Quarry Creek below the late Wenlock succession it seems likely that the Mumbil Formation ranges from Upper Wenlock to Ludlow and the Mullions Range Volcanics fall within the gap in the Quarry Creek succession. The absence of the volcanics at Quarry Creek and at other localities closer to the Mullions Range implies that interruption of deposition took place after the extrusion of the volcanics.

The Cuga Burga Volcanics which overlie the Barnby Hills Shale are on present evidence equivalent to the Bay Formation and have been placed just above the Silurian-Devonian boundary by Packham (1968) since there is a considerable thickness of shale above the occurrence of *Monograptus bohemicus* in the Barnby Hills Shale. This is a little higher than Strusz (1960) placed the Cuga Burga Volcanics. The Tolga Calcarenite which overlies the Cuga Burga at Mumbil has not been recognized in the area studied, but it has been found by Wolf (1965) and Kemezys (1959) a few miles to the north. The latter has found it to be unconformable on the volcanics. The calcarenite is apparently equivalent to or older than the shale unit in the Nubrigyn Creek area overlying the volcanics and below the limestones and lithic arenites. I suggested (Packham, 1967*a*) that the Tolga Calcarenite may be equivalent to part of the Garra Formation. This latter unit described by Strusz (1965) is a succession of shales and limestones over 4,000 feet thick, forming an outcrop extending about sixty miles north-south and about five miles east-west. Outcrop commences approximately nine miles west of the base of the Nubrigyn Formation. I also suggested (Packham, 1968) that the calcareous "Nubrigyn Formation" because of its considerable content of terrigenous sands and conglomerates may be younger than the Garra Formation in which such detritus is rare.

Based on his work on the corals, Strusz (1968) has suggested an Emsian age for the Garra Formation and from the few corals known from the "Nubrigyn Formation" a correlation with the higher beds of the Garra Formation would be indicated. Although the conodont faunas of the two formations are only very sketchily known, no great disparity in age is apparent. Rare platform conodonts (possibly *Polygnathus linguiformis dehiscens*) have been recovered from the highest parts of the Garra Formation (Philip, 1967). The upper part of the "Nubrigyn Formation" has to date yielded only small faunas but no platform types have been found. The conodonts from the lower part of the "Nubrigyn Formation" resemble those recorded from the lower beds of the Garra Formation by Philip (1967) but the corals suggest the highest levels. *Polygnathus linguiformis foveolata* incidentally, occurs in the Jesse Limestone at Limekilns. It is clear that some compromise has to be reached. Accordingly, in Table 8, it is suggested (*a*) that the Tolga Calcarenite is equivalent to the base of the Garra Formation, (*b*) that the lower part of the Garra Formation may be late Siegenian and (*c*) that the upper part is Emsian and equivalent in age to the lower part at least, of the Nubrigyn Formation but older than the Jesse Limestone.

Stratigraphic Correlations Throughout the Region

Although the fossil evidence at present available does not permit precise dating of the formations, it does, combined with the lithologically established successions, enable the relative ages of the various stratigraphic units in the region to be established with some confidence.

Commencing at the base of the succession, the oldest formation on the east, the Sofala Volcanics may be correlated generally with the Oakdale Formation, the oldest formation in the west. Whilst Ordovician graptolites occur in both formations it is possible that the formations might extend into the early Silurian. In the west there is no definite evidence of Llandovery sediments but the Tanwarra Shale of the Sofala area is best assigned to the Upper Llandovery or Lower Wenlock, at the latest. The overlying formation, the Bell's Creek Volcanics may then be correlated approximately with the Mullions Range Volcanics; both are probably Middle Silurian.

The approximate correlation of the Wenlock to Ludlow Mumbil Formation with the Chesleigh Formation follows from the lithological mapping of higher formations between Mudgee and Wellington along the Cudgegong River by Dickson (1962), Shatwell (1962) and Jones (1962). This mapping has enabled the relationship of the Cuga Burga Volcanics to the Crudine Group to be established. On the western limb of a large anticlinal structure south of Wuuluman and ten miles east of Wellington, the Cuga Burga Volcanics are overlain by slates and siltstones and above them is the Merrions Tuff. In the next anticline to the east, the Cuga Burga Volcanics are not present but are replaced by tuffs and greywackes of the Turondale Formation. This relationship indicates that the Turondale Formation and the Cuga Burga Volcanics can be correlated approximately and so too can the formations underlying them, the Chesleigh and Mumbil Formations respectively.

No formations in the Euchareena district are at present correlated with the Waterbeach Formation and the Merrions Tuff. There was apparently erosion in the west at that time.

The Cunningham Formation which is represented in the central and western parts of the region, passes laterally both eastwards and westwards into calcareous sediments. The Tolga Calcarenite and at least the lower part of the "Nubrigyn Formation" are older than the Jesse Limestone judging by the conodont assemblages (see p. 52). The possibility that the Tolga Calcarenite and the "Nubrigyn Formation" are equivalent to the Waterbeach Formation and the Merrions Tuff has not been entirely ruled out. There is, however, no clear evidence of calcareous detritus being shed into the western part of the geosynclinal region even in small quantities from the west until the deposition of some 5,000 feet of the Cunningham Formation had taken place. The highest formation in the east, the Winburn Tuff has no known equivalent in the central and western parts of the region.

Intrusive Rocks

This whole region is remarkably free from intrusive bodies compared with other parts of the Lower Palaeozoic Belt of eastern Australia. Apart from minor intrusions associated with the andesitic volcanics, the intrusives fall into two types, viz. granitic masses and dolerite dykes and sills.

Three small, massive, granitic bodies outcrop in the area: the Wiagdon Granite (named after the Parish of Wiagdon), the Millah Murrah Granite (named after the Parish of Millah Murrah) and the Bruinbun Granite (named after a locality on the Macquarie River south of Hill End). In each case the contacts are sharp and cross-cutting. These granites are probably part of, or are related to, the Bathurst Granite which outcrops very extensively to the south.

The dolerites occur in two groups roughly symmetrically placed on both sides of the region. They occur towards the margins of the central strongly cleaved zone. In the east, they are most common in the upper part of the Chesleigh Formation. They have been involved in the general low grade metamorphism of the region.

Structure

Folding

Throughout the greater part of the region, the folds have steeply-dipping axial planes. In the central part of the area a strong cleavage has developed. This cleavage first appears in the slates and as the degree of deformation increases it penetrates the coarse rocks as well. Overturned beds occur in the central part of the area but their dips are steep. It is only in the vicinity of the Wiagdon Thrust to the south of Wattle Flat that overturned beds dipping at less than 45° are encountered.

There is a general concordance between the stratigraphy and the structure of the region. The central area of maximum deposition during Crudine and Cunningham "times" is the most deformed and has been thrust eastward over a more stable area. The axial planes of the folds in the western part of the region dip to the east at angles of 70 to 80 degrees. To the east dips gradually steepen until at Hill End the axial planes are approximately vertical; still further to the east they dip steeply to the west. Along the Turon River, east of Hill End and extending to the north, is a zone in which the Cunningham Formation has been almost isoclinally folded and the overturned limbs of the folds dip steeply to the west. This gives an asymmetry to the regional structure because there is no corresponding zone to the west of Hill End. The asymmetry is further emphasized by the thrust faults which occur to the east. The Hill End anticline marks a very considerable culmination in the folds of the trough, the sediments exposed along its crest being some 20,000 feet stratigraphically lower than those in the trough of the Ophir Syncline to the west and about 15,000 feet below the highest beds in the isoclinally folded zone of the Cunningham Formation rocks to the east, about Sally's Flat.

The regional cleavage mentioned above seems to be an axial plane cleavage. It first appears at about the meridian of the Orange-Wellington railway line and extends eastwards as far as the Wiagdon Thrust. Although the rocks of the eastern side of the Wiagdon Thrust, in the area north-east of Peel, are most strongly overturned, having their axial planes dipping at 20° or so, cleavage is not developed in them.

Apart from the change in dip of the axial planes of the folds there is also a swing in strike across the region. In the north the change is from N 30°W on the western side to N 20°E on the east. The fold axes are closer packed to the south and they are generally parallel, striking approximately N 20°W. The plunge is gently towards the north in most folds.

Where grain elongations have been observed and these are common in the greywackes of the Cunningham Formation, they are approximately perpendicular to the fold axes and the bedding-cleavage intersections. Pyrite "shadows" have a similar orientation.

The metamorphism which affected the region was of low grade being no higher than green-schist facies, though there is an increase in its intensity from the margins of the area where chlorite, albite and muscovite occur, towards the centre, where biotite is common. This parallels the stronger folding and the more intense development of cleavage in the central part of the region. In addition, accompanying the northerly structural plunge there is some narrowing of the width of the biotite-bearing zone northwards. Along the southern margin of the area mapped the zone has a width of about 20 miles while at the latitude of Hill End it is about 17 miles wide.

Faulting

Minor Faults

As far as can be determined at the scale of mapping, faulting is remarkably rare in this region. Three minor faults have been mapped; one is a cross fault in the west of the region near Kerr's Creek, the second is a high-angle thrust fault six miles east of Hill End. The third is, in all probability, also a high angle thrust fault cutting off the Mullions Range Volcanics along the western side of the Mullions Range. Two localities have been found where the cleavage has been disturbed by later movements. In neither case did it seem that faulting significant on the scale of mapping had taken place. One of these localities is on the Winburndale Rivulet about half a mile from the Macquarie River and the other on the Macquarie River, one and a quarter miles upstream from its junction with Lewis Ponds Creek.

The Wiagdon Thrust System

The Wiagdon Thrust fault is the most important tectonic feature of the region. At present it is known to extend from Gulgong in the north to the Bathurst Granite near Yetholme in the south, a distance of some eighty miles. The thrust dips to the west but at varying angles. North of Sofala the dip is of the order of ten degrees—in some places even less. Near Wiagdon Hill the dip is considerably steeper and is of the order of sixty degrees. The strike likewise is very variable. North of Sofala, it is parallel to the fold axes of the area (N 30°E), and after crossing the Turon River runs approximately north-south. At Wiagdon Hill, south of Wattle Flat, the fault swings suddenly towards the south-east and then returns to N 10°E and continues in that direction to Cheshire Creek. This variation in strike, which affects the folds to the west as well as the fault, appears to be a reflection of the configuration of the mass against which the sediments to the west were folded and thrust. In the discussion of the stratigraphy of the Sofala

Volcanics some evidence was presented for the existence of a local volcanic focus near Sofala in the last stages of the vulcanism.

North of Wiagdon Hill, the thrust is apparently parallel to the bedding of the over-riding sediments, with the thrust plane occurring at about the Tanwarra Shale (sometimes within it and sometimes just below it in the Sofala Volcanics).

To the south at Wiagdon Hill, the thrust occurs within the Sofala Volcanics and several hundred feet of the volcanics have been thrust over the Chesleigh Formation. Towards the southern edge of the area mapped the fault plane passes into the Chesleigh Formation as the result of the development of an overturned anticline at the base of the overthrust mass. Two minor thrusts occur on the foreland side in the south.

Instead of the Sofala Volcanics being swept clean of later formations on the foreland side by the thrust, south-east of Wiagdon Hill the entire sequence has been preserved. This is the direct result of a southerly plunge of the folds on the foreland side which may be attributed indirectly to the suggested thinning of the volcanic pile at the top of the Sofala Volcanics. Just to the east of the thrust in this southern area the greatest degree of overturning in the whole area has been observed. Overturned dips between 65° and 20° are normal. In exceptional cases the beds are horizontal (overturned) and in one local pucker a dip of 40° to the east was observed; this overturned zone is bounded by a minor thrust which dies out to the north where the main thrust swings to the west.

North of the Turon River, the thrust structures again become complex. About a mile north of the river a new dislocation becomes apparent, this time to the west of the main thrust line. It appears within the Chesleigh Formation bringing the upper part of the Chesleigh Formation against the Bell's Creek Volcanics and then, further north, the Cookman Formation against the Bell's Creek Volcanics. The main Wiagdon Thrust is again in the Tanwarra Shale or just within the Sofala Volcanics.

The Wiagdon Thrust can be observed where it crosses the Turon River and at a number of localities about five miles north of Sofala in tributaries of Cookman Creek. In these planes there is a transitional zone from sheared andesite of the Sofala Volcanics to phyllite derived from the Tanwarra Shale. The original bedding of the Tanwarra Shale is broken down but deformed traces of it remain both on the microscopic and the macroscopic scale.

Razorback Thrust

This fault was discovered by Day (1961) four miles north of the Turon River in the vicinity of the Razorback Mine from which it takes its name. This fault is on the extreme east of the area and brings the Sofala Volcanics up against westerly-dipping Upper Devonian sandstones cutting off the western limb of the synclinal structure in which the sandstones lie. There is sufficient relief in the vicinity of the Turon River to determine that the fault plane dips steeply to the west. It is the only structure in the area for which a post-Upper Devonian age can be demonstrated.

General Summary of Depositional History

Ordovician

Ordovician rocks are exposed on the eastern and western margins of the region and andesitic volcanic material dominates both areas. The few sedimentary structures observed in the lower part of the Sofala Volcanics suggest an eastward slope of the sea-floor and the deposits represent a turbidite facies.

Higher, pyroclastic debris becomes more abundant and the presence of occasional limestone lenses in the upper part of the formation implies some shallowing but this may be only of local significance. The stratigraphy of the Oakdale Formation is unknown in detail but limestone lenses occur within the higher parts of the Upper Ordovician in the formation and at lower stratigraphic levels further west (e.g., at Molong and Bowan Park). This evidence, though fragmentary is consistent with the palaeogeographic pattern which existed in the later Silurian. The sea-floor sloped generally to the east into a region of turbidite deposition (the Hill End Trough) and commencing at the western margin of the region under discussion and extending further west, was an elevated zone (the Molong Geanticline). A second trough of turbidite deposition, the Cowra Trough, was probably in existence at this time west of the geanticline (Packham, 1967).

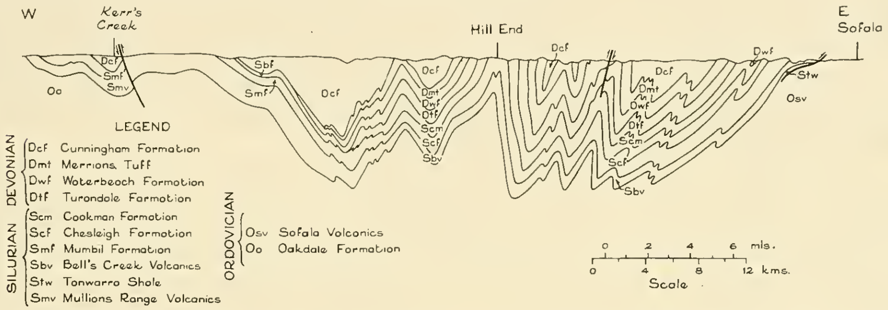

Figure 10. Cross-section from Sofala to Kerr's Creek. Section projected to depth to demonstrate stratigraphic relationship between formations in eastern and western margins of the Hill End Trough.

Silurian

It is not known whether the Sofala Volcanics and the Oakdale Formation extend into the Silurian. The possibility exists that deposition may have been interrupted by early phases of the Benambran Orogeny. The Tanwarra Shale though not definitely proven to be Lower Silurian, is probably of that age or basal Wenlock at the latest. The conglomerate at the base of the formation represents an erosional break which might be correlated with one of the two Lower Silurian orogenic phases of the Benambran Orogeny in the Orange district, the Cobbler's Creek Phase at about the base of the Llandovery or the Panuara Phase at about the middle of the Llandovery (Packham, 1968). If the correlation can be made the later one is the more likely.

The two acid volcanic formations which follow, the Mullions Range Volcanics in the west and the Bell's Creek Volcanics in the east are apparently Middle Silurian. It was suggested that the Mullions Range Volcanics lay within the gap in deposition from late Llandovery to Upper Wenlock found to occur at Quarry Creek. Mapping of the base of the volcanics has failed to reveal the presence of Llandovery beds beneath them except perhaps in the north, giving the impression that there is at least a disconformity between the Mullions Range Volcanics and the Oakdale Formation. Because of the absence of the Mullions Range Volcanics in nearby sections to the west, such as the one along the Bell River only four miles west of the 1,500 feet-thick type section of the volcanics, it is likely that the volcanics antedate the Quarry Creek Phase of the Benambran Orogeny. The regional distribution of the Bell's Creek Volcanics is also suggestive of tectonic movements post-dating them. The Chesleigh Formation which normally overlies the Bell's Creek Volcanics, overlies the Sofala Volcanics in the vicinity of Wattle

Flat, east of the Wiagdon Thrust. If these relations are the result of a local uplift, the uplift is roughly contemporaneous with the Quarry Creek Orogenic Phase.

The lower parts of the Chesleigh Formation and the Barnby Hills Shale are composed of sediments consisting of quartz, white mica and some chlorite; volcanic debris is rare. Deposits of this composition are common in Ludlow successions in the southern highlands of New South Wales, and sedimentary structures in the Chesleigh Formation in the Sofala area indicate a downward slope of the sea-floor to the east-north-east. The detritus was probably derived from Ordovician sediments (with minor contributions from granitic sources), exposed in the southern highlands of New South Wales and eastern Victoria as a result of the Benambran Orogeny. The sediments might have been transported northwards along the trend of the Benambran structures and thence into the trough. The sediments deposited on the Molong Geanticline at this stage, apart from the Narragal Limestone and its equivalents, are fine-grained (siltstones and shales) although their environment of deposition is unknown. The sediments in the Hill End Trough are coarser, consisting of interbedded slates, siltstones and fine-grained greywackes and having the typical features of a turbidite facies.

The dacitic volcanic debris in the upper part of the Chesleigh Formation, which is intermingled with detritus similar to that in the lower part, has no known equivalent in the Euchareena area. It occurs in both the Hill End and Sofala occurrences of the formation, though in the latter it is a minor constituent south of the Turon River, increasing rapidly in abundance northwards. Deposition throughout is in turbidite facies and the directional features of the sedimentary structures are consistent with those of the lower part of the formation. The volcanic centre supplying the detritus probably lay to the west or south-west of Hill End. It has not as yet been identified.

The highest formation regarded as Silurian in the Sofala area is the Cookman Formation. At its base, an important change in the pattern of sedimentation took place. Sedimentary structures indicate a reversal of the direction of source of the sediments. From this formation onwards, in the Hill End and Sofala areas, detritus came from the east. The Cookman Formation is a sequence of slates and quartz-rich greywackes. Their petrography is consistent with their having been derived from the Chesleigh Formation with minor contributions from underlying formations. The uplift of the structure to the east (the Capertee Geanticline) which considerably restricted the Hill End Trough can be regarded as part of the Bowning Orogeny and may be contemporaneous with the Yarralumla Phase (Öpik 1958). The upper part of the Barnby Hills Shale was probably deposited at the same time as the Cookman Formation.

Devonian

The new palaeogeographic pattern established with the commencement of deposition of the Cookman Formation persisted throughout the remainder of the history of the Hill End Trough. At approximately the beginning of the Devonian, vulcanism was renewed, this time on a grand scale, especially in the east. After the basal breccias of the Crudine Group, the remainder of the Turondale Formation consists of thickly bedded dacitic tuffs, greywackes composed of tuffaceous material, conglomerates and interbedded slates and siltstones. The Cuga Burga Volcanics were poured out in the northern part of the Euchareena area and northwards extending down into the Hill End Trough. Dacitic vulcanism responsible for the Bay Formation produced clastic sediments similar to those of the Turondale Formation in the southern part of the Euchareena area at about this time. The axis of the trough lay west of the Hill End Anticline as it must have done during the deposition of the Cookman Formation.

The Waterbeach Formation (the upper part of the Crudine Group) is free from evidence of contemporaneous volcanic activity. Nevertheless its greywackes are composed almost entirely of material ultimately of volcanic origin and similar to that of the Turondale Formation. Except for the sediment contained in the Ulmarrah Slump which is the most westerly occurrence of the formation, the detritus appears to have been derived from the east. The axis of the trough remained just west of the Hill End Anticline.

Wolf (1965) and Kemezys (1959) have mapped an erosional junction at the top of the Cuga Burga Volcanics and the distribution of the Cuga Burga Volcanics and the Bay Formation in the Euchareena area is compatible with such a contact. Any uplift on the western side of the trough would have probably increased the slope on the eastern side of the Molong Geanticline and initiated the Ulmarrah Slump.

The axis of the trough seems to have been at its western limit during the deposition of the Merrions Tuff, lying at least eight miles west of the Hill End Anticline and less than 16 miles east of the present outcrop of the Oakdale Formation. The thick beds of dacitic pyroclastic material of the Merrions Tuff, like those of the Turondale Formation have been interpreted as some kind of turbidite deposit. While it is possible that turbidites could have flowed up the western side of the trough to some extent, the distance was probably not significant, especially since dacite flows within the formation are found west of the Hill End Anticline. The westward shift of the axis may have been the result of infilling from the east.

Vulcanism in the trough ended with the Merrions Tuff, and with the return of normal greywacke sedimentation in the Cunningham Formation, the axis of the trough moved eastwards to about the Hill End Anticline. The sediments of the central part of the trough are fine but in the east pass into a zone in which greywackes and conglomerates are common. In some of these beds the amount of matrix is small. This distribution suggests that the slope was short and perhaps steep and that the main part of the trough was flat. The slope on the west may have been more regular since slump structures are common as far east as Hill End. The Limekilns Group which overlies the Merrions Tuff, east of the Wiagdon Thrust is correlated with the Cunningham Formation. The age of the limestone in the middle of the Group is Emsian to perhaps basal Eifelian on the basis of its conodont fauna. Judging by its fauna the Limekilns Group was deposited largely in the neritic environment. No indication of turbidite deposition has been found in it. On the west, the Cunningham Formation passes into the calcareous facies of the "Nubrigyn Formation". The transition is extremely rapid. The "Nubrigyn Formation" apparently represents a near-shore turbulent environment with algal reefs, limestone breccias, abundant coarse terrigenous material derived from a variety of sources with evidence of local vulcanism. These pass eastwards rapidly into sequences of slates and siltstones with rare greywackes, boulder horizons and calcareous turbidite beds. The basal part, if not all, of the "Nubrigyn Formation" is older than the Jesse Limestone.

Overlying the Limekilns Group in the vicinity of Limekilns and extending south for some miles is the Winburn Tuff, a formation which has lithological features very similar to those of the Merrions Tuff but is much richer in orthoclase. The field relations are strongly suggestive of a unconformity with the Limekilns Group. The Winburn Tuff is in turn overlain unconformably by quartzites and shales of the Upper Devonian Lambie Group. The latter unconformity is representative of a phase of the Tabberabberan Orogeny. The former might be regarded as related to an earlier phase of the same orogeny.

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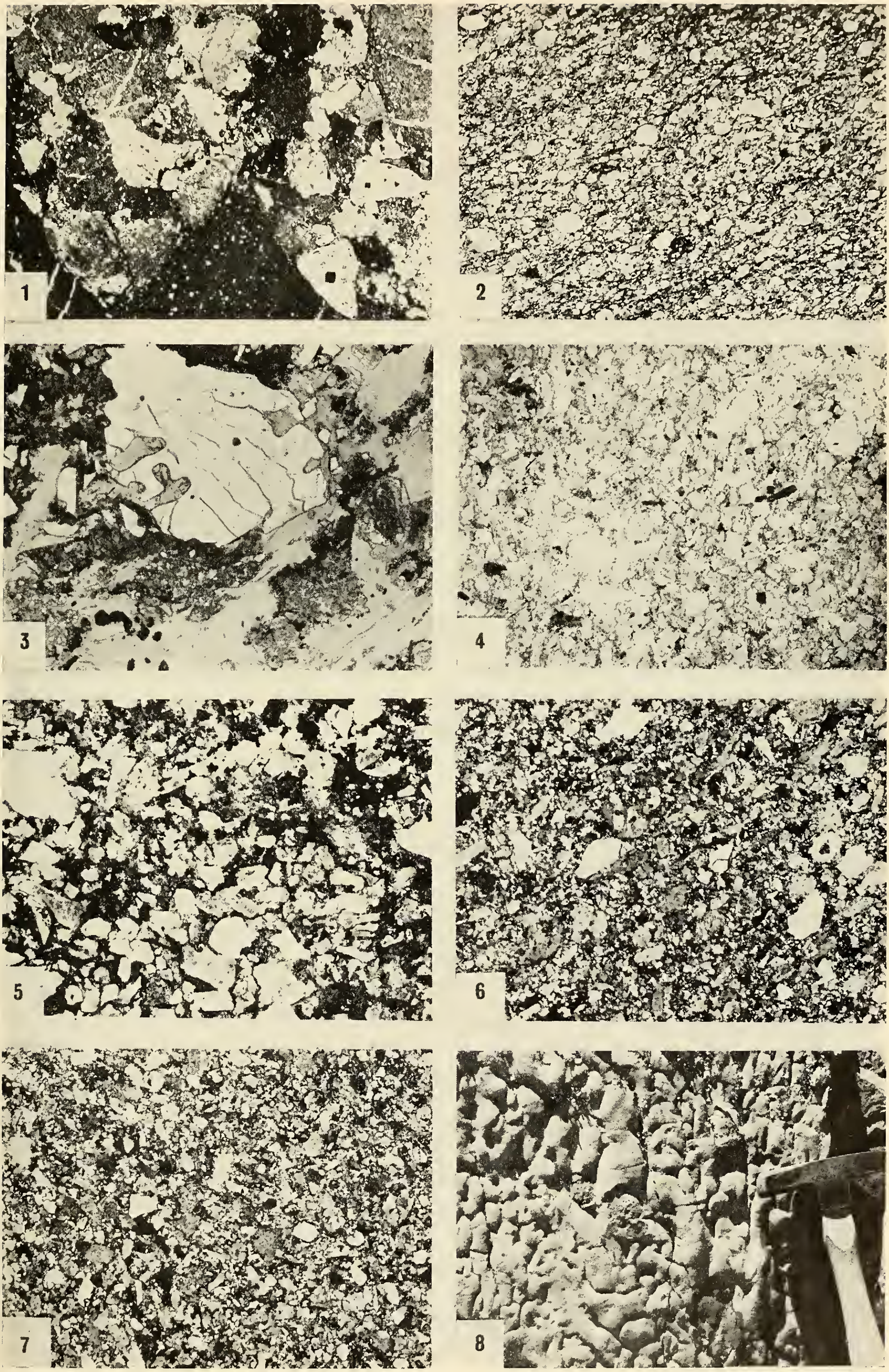

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